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METHODOLOGIES FOR OPTIMAL RESOURCE ALLOCATION TO THE NATIONAL SPACE PROGRAM AND NEW SPACE UTILIZATIONS

FINAL REPORT

VOLUME 1

TECHNICAL DESCRIPTION

19 NOVEMBER 1971

PREPARED UNDER CONTRACT NAS2-5202

FOR

ADVANCED CONCEPTS AND MISSIONS DIVISION
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
AMES RESEARCH CENTER
MOFFETT FIELD, CALIFORNIA

BY

LOCKHEED MISSILES & SPACE COMPANY
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FOREWORD

This report volume describes the analytic methodologies of a computer model for optimal allocation of resources to the national space program, and of criteria and their application to evaluate potential new space program directions. This study is being performed for the National Aeronautics and Space Administration under Contract NAS2-5202. The study is monitored by Mr. R. E. Slye and Mr. Harold Hornby of the Advanced Concepts and Missions Division of the Office of Advanced Research and Technology.

Individuals of Lockheed Missiles & Space Company, Sunnyvale, California, who contributed to this study are L. F. Fox, project leader; C. J. Golden, key technical member; and W. T. Lew.

ABSTRACT

The optimal allocation of resources to the national space program over an extended time period requires the solution of a large combinatorial problem in which the program elements are interdependent. The developed computer model uses an accelerated search technique to solve this problem. The model contains a large number of options selectable by the user to provide flexible input and a broad range of output for use in sensitivity analyses of all entering elements. Examples of these options are budget smoothing under varied appropriation levels, entry of inflation and discount effects, and probabilistic output which provides quantified degrees of certainty that program costs will remain within planned budget. Also during this study phase criteria and related analytic procedures were established for identifying potential new space program directions. Used in combination with the optimal resource allocation model, new space applications can be analyzed in realistic perspective, including the advantage gain from existing space program plant and on-going programs such as the space transportation system. The developed model and the new commodity decision criteria can readily be adapted to other resource allocation areas by particularizing parameters and making changes to model analytics.

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SUMMARY

This document is Volume 1 of a two volume report titled Methodologies for Optimal Resource Allocation to the National Space Program and New Space Utilizations. Volume 2 provides details on the computer program developed and exercised during this study. This volume provides a technical description of data collection and analysis, the current version of the computer model and its operation, and the development of decision criteria and related analytic procedures for evaluating potential new space program directions.

The present improved version of the model quantitatively handles all significant cost and performance parameters that enter the national space program - payloads; stages and vehicles; launch facilities and other operational plant; expendable, partially reusable and fully reusable vehicles in the same mix; parameters that apply to reusables such as refurbishment, on-orbit time, turn-around time, number of units for varying levels of traffic; and others. The effect of external economics can be included - parametric funding levels, inflation and discounting. Essentially all of these parameters are interdependent. The developed model uses an accelerated search technique that ensures a global optimal solution based on least total cost.

The computer model's logic structure is divided into independant subroutines. This feature and the large number of options that can be selected provide a high degree of flexibility. Among the selectable options are deterministic or probabilistic input/output, budget smoothing under yearly spending levels, and learning both in cost and time. During this study the model has been operated on problems of realistic size, i.e. high traffic loads, a large mix of existing and potential stages and vehicles, and a mission model combining both planned and generic missions over a 20 year period.

Also during this work phase decision criteria and related analytic procedures were developed for identifying potential new space program directions. Used in combination with the optimal resource allocation model, potential new space applications can be analyzed in realistic perspective, including the advantage gain from the national investment in existing space program plant and contemporary on-going programs such as the space transportation system. The profit and benefit gain, including environment improvement, produced by a new application can be determined. Generic growth mission models superimposed on presently planned national space mission models were used to test the decision criteria. The approach developed provides a systematic method for examining new space applications which can exploit the national investment in space and evaluate new concepts having potential for increasing national productivity. Further, combined use of the resource allocation model and the new directions criteria is uniquely suited to evaluating the effects of varied traffic levels for the reusable space transportation system.

The potential of the resource allocation model and new commodity decision criteria for application to other optimal assignment areas was assessed. This analysis has shown the model and decision criteria can be readily adapted to other resource allocation problems by particularizing parameters and making changes to model analytics.

Section 1
INTRODUCTION

1.1 BACKGROUND

During prior phases of work under contract NAS2-5202, directed by the NASA Advanced Concepts and Missions Division, a computer model with deterministic or probabilistic input/output options was developed for use in evaluations of the national space program. Using accelerated search and special techniques to reduce computer storage and run time, the model evaluates the large number of interdependent factors which enter this large scale problem.

The computer program has been developed on a modular basis with different analytical functions incorporated in independent subroutines. This logic structure and the large number of options that can be selected for execution under program control provide the decision maker with an analytical tool having a high degree of flexibility. The model quantitatively handles all significant cost and performance parameters that enter the national space program - payloads; stages and vehicles; launch facilities and other operational plant; expendable, partially reusable and fully reusable vehicles in the same mix; parameters that apply to reusables, such as refurbishment, on-orbit time, turn-around-time, number of units for varying levels of traffic; and others. A broad range of output data is available for sensitivity analyses of all entering elements.

Included in the model are the effects of learning (cost and time) and variable inflation, a reduced historical data base to quantify cost uncertainty, and the ability to smooth expenditures under year-by-year budget constraints. The accelerated search feature ensures a global optimal solution based on least total cost.

This broad range of capabilities provides the advanced planner with a powerful tool for optimal allocation of resources to the national space program. Additional descriptive details on the analytic techniques of the model are provided in Refs. 1 and 2.

1.2 STUDY OBJECTIVES

Under prior phases of study three areas were identified in the development and operation of the model described in section 1.1 above which could significantly increase its effectiveness as an analytical tool. The objectives were to:

(1) Extend the model analytically to incorporate more specific statistical relationships based on a study in greater depth of the historical data base.

(2) Exercise the model using both deterministic and probabilistic options on problems of realistic size - i.e., high traffic loads, a large mix of potential stages and vehicles, a combination of both planned and generic space missions over an extended period, and parametric levels of space program funding and inflation.

(3) Define criteria and develop an analytical method for evaluating new concepts for growth commodities and services for potential exploitation in the space program.

During the present phase of this Contract the above objectives were accomplished. The following significant elements of work were performed:

- Updated input data were collected from a wide range of sources to provide for parametric exercising of the model
- Historical data on spacecraft and payload were analyzed. A quantified basis was established for determining these mission related costs for future missions
- Improved statistical correlation was defined between advanced system cost elements. This modification and the conversion of the model to a three parameter log-normal distribution for program elements provide a cost prediction basis for advanced programs which closely matches the historical data base.
- Production exercising of the model established the capability of the model to handle large scale analyses and to output sensitivity data for use by the decision maker
- Decision criteria and related analytic methodology were developed to identify and evaluate new potential space program directions

This current phase of work has demonstrated the effectiveness of the model to provide optimal allocation of available resources to the national space program.

In addition the flexibility of the model has been assessed for use in other optimal assignment areas. This analysis has shown that the basic model can be readily adapted to other resource allocation problems by particularizing the parameters and making minor modifications to the model analytics.

Section 2
INPUT DATA

The data required to exercise the vehicle assignment computer model have been collected from various published sources under the direction of the Advanced Concepts and Missions Division. These data include (1) parameterized budget constraint and associated base cost options including the effect of inflation, (2) multiple options of unmanned and manned mission profiles for the time period 1973-1992, (3) performance characteristics associated with stage and launch vehicle candidates including fully reusable, partially reusable and expendable configurations, and (4) cost breakdowns for these mission options and vehicle candidates including cost growth factors and statistical correlation relationships which were analyzed historically.

Each mission and launch vehicle program was researched for general information to gain an understanding of what elements were included in each cost estimate. The cost data was then formatted to be compatible with the computer model input requirements. Statistical parameters associated with these data including cost growths were updated as a reference for future runs and as a basis for extension of the model. A description of the basic input used in recent production runs is presented in the following subsections.

2.1 APPROPRIATION LEVELS

Three budget options indicated in Fig. 2-1 were selected for consideration on a parametric basis as possible future NASA funding levels. These budget options were derived by extrapolating the curve of past annual NASA appropriation levels using the following three growth characteristics:

(1) Appropriation level has an overall growth rate of 7½%

(2) Appropriation level has an overall growth rate of 2%

(3) Appropriation level is a straight line extrapolation of recent historical levels

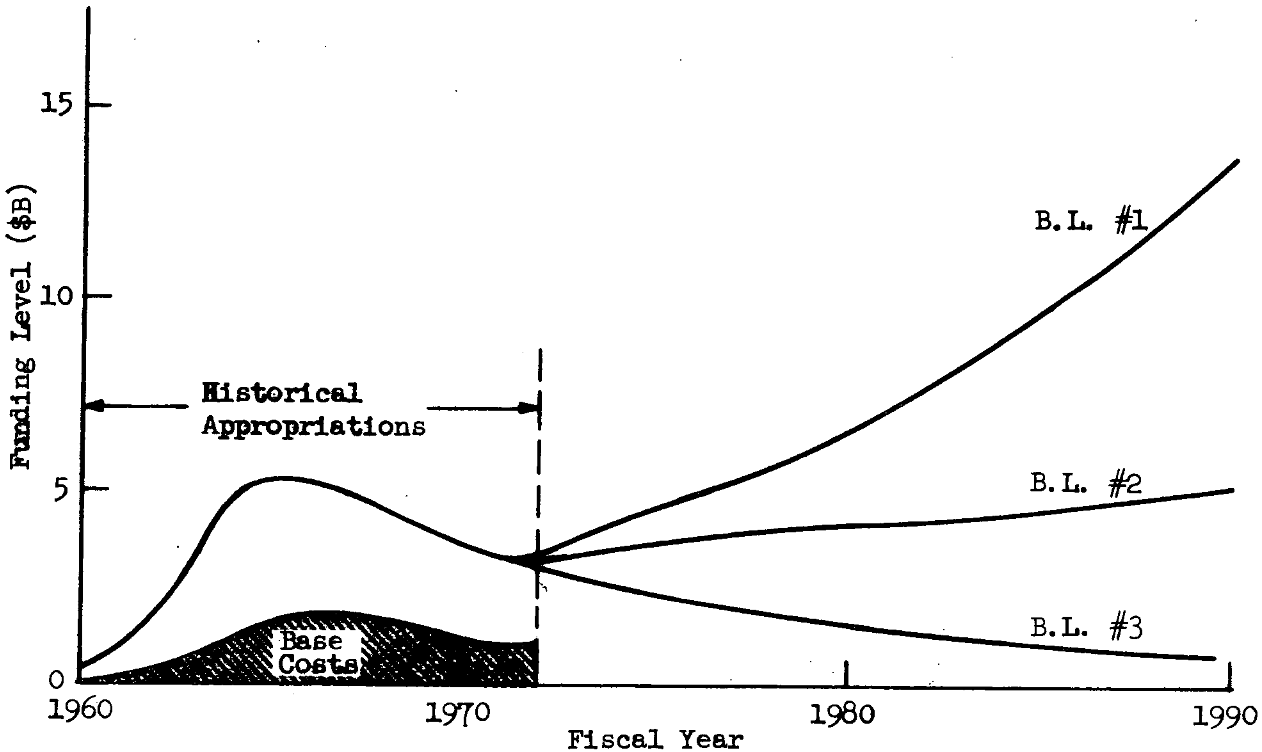

Fig. 2-1 Budget Level Options

An average inflation factor of 3% per year is assumed over the 20-year period 1973 to 1992.

Base costs which consist of ART, TDA, Technology Utilization and University Affairs, Construction of Facilities, and RPM expenditures are considered a function of the total appropriation level. The history of base cost levels is shown in Fig. 2-1. Base costs for each of the three budget options have been extrapolated based on historical data. For years after 1973 the following breakdown in base costs was used:

ART - Advanced Research and Technology	10% of total appropriation
TDA - Tracking and Data Acquisition	$.3 billion fixed
RPM and R&D Support - Research and Program Management	25% of total appropriation

The actual funds available for SSA and MSF programs is the difference between the total appropriations level and the base cost level. These discretionary funds are represented by the unshaded area under each curve in Fig. 2-2 for each of the three budget options. Since budget levels are shown in dollars for that year, inflation, if any, is implicitly included in all budget levels. Thus, if an inflation rate is applied to the base level the amount of discretionary funds is reduced.

The handling of budget levels and base costs as outlined above permits the evaluation of various space options both with and without the effect of inflation.

2.2 MISSION PROFILES

For each budget option considered, several mission profiles covering the years 1973 through 1992 were investigated to discover what over-all national space program could be completed under the specified budget constraints. The missions in each profile were selected from a list which has two sections:

(1) NASA-authorized missions, and

(2) Future (post 1975) mission categories

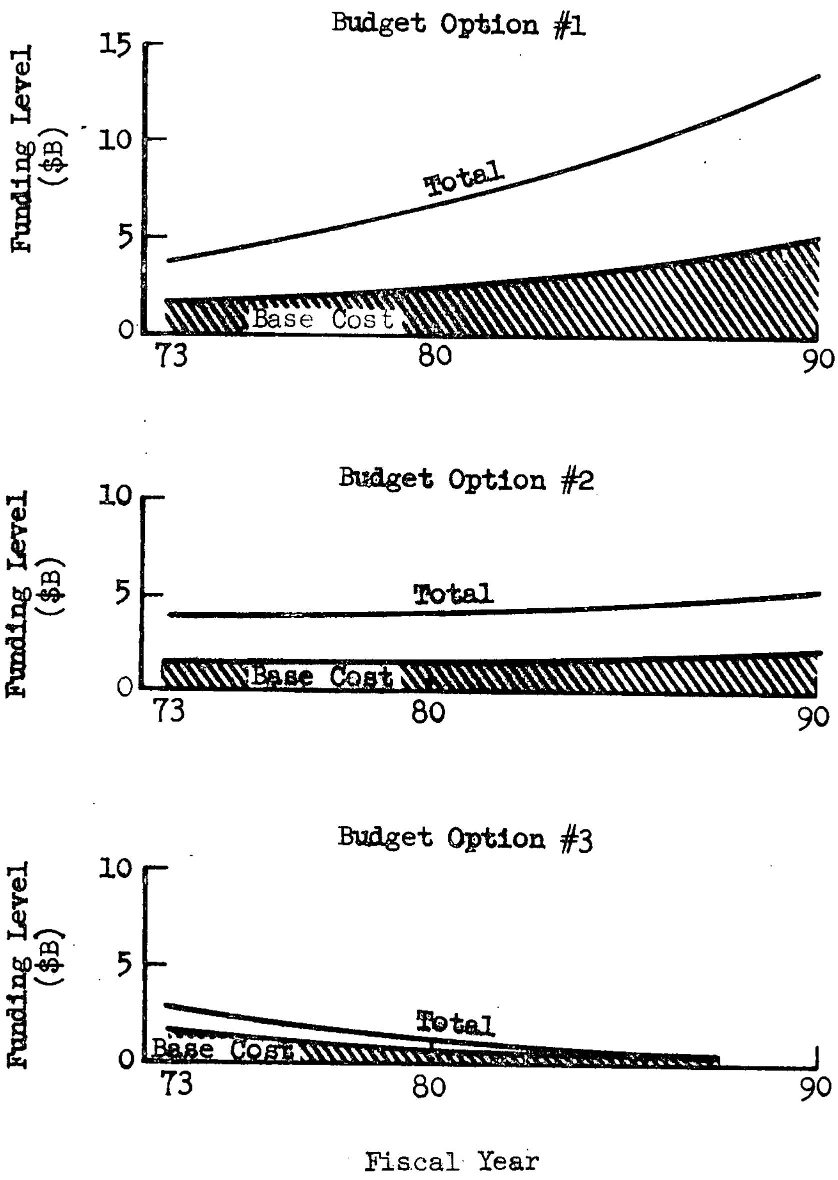

Fig. 2-2 Base Cost Levels

The second section was developed to provide flexibility in planning and missions scheduled in the post-1975 time period are identified only by general categories of utilization and averaged performance characteristics.

2.2.1 Authorized Missions

Tables 2-1 and 2-2 list the authorized missions, their requirements and cost breakdowns. No Scout missions were included since their impact on the total budget level is not significant. Requirements for these missions were identified from published sources. Mission cost data was determined for some major programs in terms of spacecraft, experiments, and operations categories. These costs were analyzed and combined so that they would fit one of the cost categories shown in Table 2-2. Complete cost distributions were available for the TDRS, Lunar Orbiter, OAO, and Pioneer F-G programs. Predicted breakdowns were also available for two Grand Tour missions.

For programs in which cost breakdowns were otherwise generally unavailable in sufficient detail to identify specific program elements with their related cost estimates, an approach was developed to standardize mission (spacecraft and experiments) program costs. Using this procedure a reasonable estimate can be made for these program elements given the total program cost and the number of scheduled launches. The following breakdown is one derived from available detailed breakdowns of several completed mission programs. This breakdown is applicable to an unmanned scientific program involving two launches of similar spacecraft, but with different experimental packages on each launch.

<u>Total Program Cost Breakdown</u> (excluding launch costs)

Spacecraft cost	68 percent
Experiment package cost	22
Program management cost	10
Total program cost	100 percent

<u>Spacecraft Cost Breakdown</u>

Spacecraft R&D	55 percent

Spacecraft procurement (Per unit 12 percent)	36
Operations (Per launch 2.5 percent)	5
Sustaining cost	4

Experiment Cost Breakdown

Experiment R&D (2 launches) (Per launch 22.5 percent)	45 percent
Data analysis (Per launch 16 percent)	32
Hardware procurement (Per unit 7.7 percent)	23

Cost Breakdown for Computer Model Input (excluding launch costs)

A. Non-recurring Cost

Spacecraft R&D	.55 x .68 x Total Program Cost
Spacecraft prototype hardware	.12 x .68 x Total Program Cost
Experiment prototype hardware	.077 x .22 x Total Program Cost
Non-recurring Cost =	47 percent x Total Program Cost

B. Recurring Cost

Spacecraft unit hardware procurement	.12 x .68 x Total Program Cost
Spacecraft operations	0.25 x .68 x Total Program Cost
Experiment R&D	.225 x .22 x Total Program Cost
Experiment unit hardware procurement	.077 x .22 x Total Program Cost
Experiment data analysis	.16 x .22 x Total Program Cost
Recurring Cost =	20 percent x Total Program Cost
	x 2 launches
	40 percent x Total Program Cost

C. Sustaining Cost

Program management	.10 x Total Program Cost
Sustaining engineering	.04 x .68 x Total Program Cost

Table 2-1

NASA AUTHORIZED MISSIONS

Mission	Launch Year	No. of Launches	Gross Wt. (lbs)	Expt. Wt. (lbs)	Satellite Lifetime	Assigned Vehicle	V_c (fps)
Mariner H - I	71	2	2200	138	3 mos Mars Orb.	Atlas Cent.	39000
Mariner J	73	1	820 - 1030	100 - 130	7 mos	Atlas Cent.	39000
Pioneer F - G	72 - 73	2	550	66	30 Days Aft. Enc.	Atlas Cent.	49000
Viking A - B	75	2	7600		90 Days	Titan Cent.	39400
Helios A - B	74 - 75	2	500	110	1.5 Yrs.	T3D Cent.	47000
ERTS A - B	72,73	2	1800	450	1 Year	Thor Delta	26500
GEOS C	72	1	460	141	1 Year	TAT Delta	27000
ATS F - G	73,75	2	2050	600	2 Years	T-3C	33600
Nav. Traffic	75	2	1520	600		Thor Delta	33600
Nimbus E - F(WTR)	72,73	2	1464	325	1 Year	Thor Agena	29000
SMS A - B	72,73	2	535	185	3 Years	Thor Delta	33600
INTELSAT	71,72 73,74	2,3 1,2	1000		7 Years	Atlas Cent.	33600
ARINC	77	2	Assume same as Nav. Traffic				
OAO B - C	72	1(C)	4678	982	1 Year	Atlas Cent.	26300
OSO (H thru K)	71,73 74,76	2 2	1365	465	6 mos	Thor Delta	26000
ATM Explorer	73,74,75	3	1000	100	1 Year	Thor Delta	28000
ISIS A - B(WTR)	71	1(B)	585	151	1 Year	Thor Delta	25500
RAE A - B	72	1(B)	725	112	1 Year	Thor Delta	36000
IMP H,I,J	72,73	2	909	167	1 Year	Thor Delta	36000
HEAO A - B	74,75	2	19750		1 Year	T-3C	25200
APOLLO	71,72	2,2	95000			S - V	36000
SKYLAB A	72	1	190000		8 mos	S - V	26500
SKYLAB SUPPORT	72,73	1,2	25000		2 mos	S - 1B	26500

Table 2-2

NASA Authorized Missions - Cost Distributions ($M)

Mission	Rec. Cost* Hdwr.	Rec. Cost Oper.	Rec. Cost Data	Sust. Cost Per Yr.	Yrs. Sust.	NR Cost	Dev. Yrs.	Total Prog. $
Mariner H - I	16.3	2.11	4.45	2.7	2	68.9	5	120
Mariner J	23.3	3.48	7.34	3.35	2	58.2	4	99
Pioneer E - G	13.9	1.65	3.69	2.77	2	61.0	4	105
Viking A - B	112.2	14.6	30.8	12.5	3	477.3	7	830
Helios A - B	1.4	.18	.39	.19	2	6.13	5	10.5
ERTS A - B	20.2	2.64	5.55	3.38	2	86.5	5	150
GEOS C	3.4	.43	1.7	.34	1	6.8	4	12.7
ATS F - G	28.0	3.0	6.3	3.3	2	94.9	6	176
NAV Traffic	16.2	2.1	4.45	2.7	2	69.0	5	120
Nimbus E - F	13.75	1.85	3.9	2.03	2	62.3	6	105.4
SMS A - B	3.85	.27	.4	.71	2	17.5	4	28
INTELSAT IV	← 3.6 →					30.0		33.6
ARINC	16.2	2.1	4.45	2.7	2	69.0	5	120
OAO B - C	25.35	2.85	3.7 **	4.6	4	86.3 PD	4	172
OSO (H thru K)	10.5	1.58	.19	2.1	3	49.8 PD	8	105
ATM Explorer	6.65	1.03	.13	1.2	2	26.0	5	51.8
ISIS A - B	3.21	.22	.15	.23	2	6.7	7	14.3
RAE A - B	3.78	.72	.77	.36	2	9.0 PD	8	20.3
IMP H,I,J	2.6	.4	.33	.30	2	PD		10.6 +NR
HEAO A - B	27.2	7.05	7.4	5.4	1	108	6	207.6
APOLLO	← 389.3 →			105	2	PD		988.6
SKYLAB A	← 300 →			8.2	5	809.9	5	1,150.9
SKYLAB SUP.	← 73.5 →			8.1	5	200	5	460.5

* All costs in $M(millions)

** Three years of data acquisition/reduction costs

Sustaining Cost =		13 percent x Total Program Cost
	Total	100 percent

Using cost distributions, such as the one above, as a guideline and any actual costs which were available for a particular program, the remaining unmanned authorized programs were analyzed to produce the cost distributions in Table 2-2. Cost breakdowns for the manned missions were based upon estimates. PD means that the cost category designated has already been paid. Sustaining costs may be extended after the last year of launch. The total number of years in which sustaining costs are required is shown under YEARS SUST. All costs are in millions of dollars.

2.2.2 Future Mission Categories

Any detailed listing of future missions will not provide adequate consideration of all potential missions. Therefore, to provide flexibility in future mission planning, missions identified for the 1975-1992 time period were combined in terms of general categories. These categories or future directions of effort are listed below.

Table 2-3

FUTURE MISSION CATEGORIES

Unmanned	Code	
Earth Orbital Applications	UMEO+C	(Unmanned Earth Orbital + Communications)
Earth Orbital Science	P+AWOH	(Physics + Astronomy except for HEAO-type missions)
	SCILAB	(Science Lab)
Planetary Exploration	UMPLNW	(Unmanned Planetary With Sample Return)
	UNPLWO	(Unmanned Planetary Without Sample Return)
Unplanned	UNPLAN	(Provisions for future missions whose specific function is presently undefined)

Manned

Earth Orbital Operations	MEOO	(Manned Earth Orbital Operations)
	MEOSUP	(Support)
Space Base	SPBASE	(Space Base)
	SPBASU	(Support)
Lunar Exploration	MANLUN	(Manned Lunar)
	MALUSU	(Lunar Support)
Planetary Exploration	MANPLA	(Manned Planetary)
	MAPLSU	(Manned Planetary Support)

Typical missions which have been grouped into the category identified as Earth Orbital Application Missions are earth resources technology, communications, navigational and meteorological satellites, etc. Table 2-4 lists the type of mission grouped into each unmanned category. Each mission itself represents a "weighted" average of all missions of that type; i.e., payload weight and characteristic velocity for each mission listed represents an average of these characteristics over all similar missions. An example is Flybys under the Planetary Exploration heading. The following individual missions were included in the investigation to determine the "average" characteristics of a Flyby mission.

Destination	Duration (days)	Mass in Earth Orbit (kg)*
Mercury	110	900, 3000, 5500, 10,000
Venus	160	500, 1800, 3400
Mars	290	340, 550, 1900, 3400
Jupiter	950	1500, 2300, 6500, 11,000
Saturn	1780	4700, 6000, 14,000, 22,000
Comet	200	1800
Solar	95	340, 1900
Ceres	430	750, 1130, 3600, 6200
Uranus	4200	9000, 10500, 24000, 34000

Table 2-4

MISSION MAKEUP FOR EACH GENERAL CATEGORY

Category		Gross Wt. (lbs.)	V_c (fps)	Number of Launches Per Program
Earth Orbital Applications				
Earth Resources		2000	26500	2
Meteorology	1	1000	33600	4
	2	2000	29000	2
	3	700	27000	2
Small Applications		1000	27000	4
Communications	1	500	27000	2
	2	5000	33600	4
	3	1500	33600	8
	4	1500	33600	2
	5	3000	33600	4
Average		2100	30000	4
Earth Orbital Science				
Solar Observatory		1800	26000	4
Astronomical Observatory		5000	26300	4
Explorer Type	1	750	26500	5
	2	850	26500	4
	3	900	26500	3
Geophysical Observatory		1000	36000	4
Science Lab		25000	27000	2
Average without Science Lab		1300	26500	4
Science Lab		25000	27000	2
Planetary Exploration				
Flybys		2860	40000	2
Orbiters		2500	46000	3
Grand Tours		1500	52000	2
Solar		900	52000	2
Probes		2860	49000	3
Sample Return		7500	60000	2
Average without sample return		1380	48000	2
Average with sample return		3240	50000	2

Neptune	6000	13,000, 16,000, 28,000, 40,000
Pluto	6000	25,000, 26,000, 43,000, 62,000

After the "average" characteristics of each type mission were determined, these characteristics were averaged again using expected frequencies of launch to determine expected requirements for each category of mission. Where an obvious distortion of the general category requirement is caused by a single mission, this mission is taken out of that category (e.g., Science Lab under heading Earth Orbital Science).

The expected requirements for future manned missions were determined in the same manner except that the number of missions to be averaged in each category was relatively small. The seven categories of future mission directions are presented in Table 2-5 along with an eighth category designated "Unplanned." Provision for mission concepts which have not yet been developed or considered as specific potential missions has been made by providing this "Unplanned Mission" category in the mission model. The expected requirements for this category were found by averaging the requirements of all the future missions considered in this analysis. The number of launches in this unplanned category was taken as an average of the total launches scheduled in other categories. Historically, NASA launches have been equally divided between Explorer size payload and large payload missions. This factor influenced the averaging process.

Cost breakdowns for the unmanned future categories were found using the same procedure outlined in section 2.2.1. In addition data analyses have

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* Due east launch from ETR into a 100 n.m. circular orbit. Mass shown is gross P/L (i.e., spacecraft + payload + additional Δv required for mission).

Table 2-5

NASA Mission Categories (1975-1992)

Mission		Launch Year Input	No. Launches Per Program	Gross Wt. (lbs)	V_c (fps)	NR ($M)	Dev. Yrs.	Sust. Per Yr. ($M)	Rec. ($M)	Total Prog. Cost ($M)
Unmanned										
Earth Orbital Applications	No. 1	77-80	4	2,100	30,000	119.3	4	10.36	32.75	292
	2	79-82	4	"	"	"	"	"	"	"
	3	81-84	4	"	"	"	"	"	"	"
	4	83-86	4	"	"	"	"	"	"	"
	5	85-88	4	"	"	"	"	"	"	"
	6	87-90	4	"	"	"	"	"	"	"
	7	89-92	4	"	"	"	"	"	"	"
Earth Orbital Science	1	77-80	4	1,300	26,500	72.3	4	4.38	11.45	136
	2	79-82	4	"	"	"	"	"	"	"
	3	81-84	4	"	"	"	"	"	"	"
	4	83-86	4	"	"	"	"	"	"	"
	5	85-88	4	"	"	"	"	"	"	"
	6	87-90	4	"	"	"	"	"	"	"
	7	89-92	4	"	"	"	"	"	"	"
Lab	8	79-80	2	25,000	27,000	150	4	20.0 (3)#	40	290
	9	85-86	2	"	"	"	"	"	"	"

Number of years sustained

Table 2-5 (Continued)

NASA Mission Categories (1975-1992)

Mission	Launch Year Input	No. Launches Per Prog.	Gross Weight (lbs)	Vc (fps)	NR ($M)	Dev. Yrs.	Sust. Per Yr. ($M)	Rec. ($M)	Total Prog. Cost ($M)
Unmanned									
Planetary Exploration (With or w/o sample return) No. 1	81-82	2	1,380	48,000	224.9	5	20.0	61.2	387.3
2	83-84	2	2,362	50,000	"	"	"	"	"
3	85-86	2	2,362	"	"	"	"	"	"
4	87-88	2	2,362	50,000	224.9	5	20.0	61.2	387.3
5	89-90	2	3,240	50,000	516.8	5	38.5	148.1	890
6	91-92	2	"	"	"	"	"	"	"
Grand Tour	76-79	4	1,500	52,000	338.4	5	30 (6)	95.4	900.
Unplanned									
No. 1	77-78	2	2,100	30,000	255.5	5	26.7	88	485
2	82-83	2	"	"	"	"	"	"	"
3	87-88	2	"	"	"	"	"	"	"
4	91-92	2	"	"	"	"	"	"	"
Manned									
Earth Orbital Operations No. 1	78	1	190,000	28,500	3,690	7	217.3 (4)	600	5,159
2	87	1	"	"	"	"	" (7)	"	"
Space Base	85	1	200,000	28,500	10,000	7	550 (10)	640	16,140†
Lunar	88	1	200,000	28,500	17,500	6	800 (10)	720	26,220†
Planetary	91	1	200,000	28,500	17,500	6	800 (8)	720	24,620†
Support Missions	As required		25,000	27,000	-	-	-	75-90*	75-90X No. Flts.

* $75M support launch for Earth Orbit Operations
$80M support launch for Space Base Operations
$90M support launch for manned lunar or planetary

† Without support

provided the spacecraft/experiment breakdown of unit and R&D costs for some near earth satellites and unmanned lunar and interplanetary missions.

Spacecraft/Experiment (S/E) R&D Cost Ratios

Mission	S/E R&D Cost Ratios	S/E Unit Cost Ratios
Near Earth Satellites	2.70	1.86
Unmanned Lunar	1.94	2.85
Unmanned Interplanetary	6.14	5.67

The near earth satellite data include costs for the OAO, OGO, OSO, IMP, Pioneer, Sert, Advent, Syncom, and Relay programs. The lunar missions include data from Rangers 1-9, Surveyor, and the Lunar Orbiter. The interplanetary missions include data from Mariner II, Mariner IV, and Mariner '69.

These data indicate that the R&D cost allocation for experiments decreases as the spacecraft required for the mission increases in complexity, e.g., the spacecraft/experiment R&D cost ratio is 2.7 for near earth satellites and is 6.1 for interplanetary type missions. The R&D cost breakdown for the lunar missions is biased because the data include nine Ranger missions which essentially used a single spacecraft design, thus allowing a larger proportion of R&D costs to experiments. The spacecraft/experiment cost breakdown shown is as expected for increasing complexity of the spacecraft.

Development and sustaining costs for scientific experiments associated with a manned operation are included in the recurring and sustaining costs, respectively, of the corresponding operation and its support. For example, the space base would require $250M/year sustaining by itself; experiments to be performed at the base would require another $300M/year sustaining and $10B total would be required for experiment development cost. Experiment and sustaining costs would be amortized over the life time of the base by including it in support costs.

The manned lunar operation includes development and sustaining costs for the modifications required to the earth-to-orbit shuttle and the development of a space tug. Development of a tug and shuttle modifications would require $4B of non-recurring cost with $100M/year for sustaining. The lunar orbit station would require $3.5B with another $100M/year sustaining. The lunar surface base costs $10B development and $250M/year sustaining. Lunar orbit station and lunar base experiments would require approximately another $370M/year for sustaining. The experiments associated with the lunar program would cost approximately $14.5B for development. This development cost is amortized over the lifetime of the program by including it in support costs.

Costs for the Manned Planetary Category were derived from a Mars planetary mission. Included in these costs are the development of a nuclear stage, Mars excursion module, manned roving vehicle, and scientific experiments associated with this program.

2.3 LAUNCH VEHICLE CANDIDATES

The launch vehicles considered for these production runs are described in this section in terms of their performance characteristics and estimate of cost by category.

Some explanation of the abbreviations used for launch vehicle names follow.

SLV	Standard launch vehicle, i.e., Atlas
IMDE	Improved Delta
TAT	Thrust Augmented Thor - (3 castor or 6 castor)
AG-D	Agena D
AGLT	Agena Large Tank
Cent	Centaur
T-3B	Titan 3B
T3D7	Stretched Core I with 7-segment, 120" solid strapons
156-5(4)	156" solid with 5,4 segment solid motors
120-10(7)	120" solid with 10,7 segment solid motors
LS4B	Low cost SIVB; weighs 4500 lbs less than present configuration and has simplified guidence system
R25B	Reusable booster

R250	Reusable propulsive second-stage orbiter
MSHT	Modified Shuttle similar in cost to stage and one-half or single-stage-to-orbit with S/C concepts
S/C	Non-ascent-propulsive reusable spacecraft (can have on-orbit propulsion)
SIC4	SIC with 4F1 engines
CSM	Commend Service Module
BII	Burner II with 2300 lbs. of solid propellant

2.3.1 Launch Vehicle Performance Data

Launch vehicle performance characteristics reflect the latest data as presented in the January 1971 revision of the NASA-OSSA document "Launch Vehicle Estimating Factors."

Points specified on the payload vs. characteristic velocity curve corresponding to performance requirements of interest are presented in Table 2-6 for the candidate vehicles.

Some vehicles were omitted because either they could not accomplish any mission on the list in Section 2.2 (e.g., Scout), or they had similar performance and cost characteristics to a vehicle already included (e.g., uprated Titan with winged spacecraft is very similar to 156(5)-LS4B-S/C on list). Therefore, conclusions relating to any specific vehicle will also apply to any vehicle with the same performance and cost characteristics. All fully reusable and partially reusable vehicles were given the capability of 40,000 lbs. payload at 27,000 fps. Costs for these vehicles were determined on the basis of this capability. If mission requirements exceed shuttle-only capabilities, or if the mission destination lies outside the shuttle operating region, then the addition of an upper stage provides one alternative for mission completion. In this case the net shuttle payload consists of the user's payload (spacecraft and/or cargo), a spacecraft/upper stage adapter, an upper stage, and whatever payload service equipment that may be required. The gross shuttle payload is the sum of the net shuttle payload and the normal shuttle/payload

Table 2-6

LAUNCH VEHICLE PERFORMANCE CHARACTERISTICS

		P/L (lbs) at 25,500 fps	P/L (lbs) at 40,000 fps	Additional Data
1	SLV-3C Cent	11,500	900	100 lbs at 42,300 fps
2	SLV-3C Cent B-II	11,500	1800	420 lbs at 50,000 fps
3	TAT(3C) IMDE	3,000	400	300 lbs at 35,000 fps
				1150 lbs at 30,000 fps
4	TAT(3C) IMDE TE 364	3,000	420	850 lbs at 35,000 fps
5	TAT(3C) AG-D	3,600	-	420 lbs at 34,000 fps
6	TAT(3C) AG-D B-II	3,600	240	
7	TAT(6C) IMDE	3,600	-	1450 lbs at 30,000 fps
				300 lbs at 35,000 fps
8	TAT(6C) IMDE TE 364	4,000	500	1100 lbs at 35,000 fps
9	T-3B AG-D	9,500	550	2600 lbs at 34,000 fps
10	T-3B AG-D BII	9,500	940	345 lbs at 45,000 fps
11	T-3B Cent	11,600	1200	100 lbs at 43,000 fps
12	T-3B Cent B-II	11,600	1600	100 lbs at 51,500 fps
				3000 lbs at 36,100 fps
13	T-3D	26,000	750	7500 lbs at 33,600 fps
				2400 lbs at 38,000 fps
14	T-3D AG-D	27,000	3800	1100 lbs at 46,000 fps
15	T-3D AG-D B-II	27,000	3800	1400 lbs at 46,000 fps
16	T-3D AGLT	31,000	4300	900 lbs at 48,000 fps
17	T-3D AGLT B-II	31,000	4300	1300 lbs at 48,000 fps
18	T-3D Cent	35,000	7500	1400 lbs at 48,500 fps
				800 lbs at 50,000 fps
19	T-3D Cent B-II	35,000	7500	2000 lbs at 50,000 fps
20	T-3D Transtage(T-3C)	28,000	2300	9800 lbs at 33,600 fps
				3400 lbs at 38,700 fps
21	T-3D (7)	38,000	2200	450 lbs at 42,000 fps
22	T-3D (7) Cent	46,000	10,000	1300 lbs at 51,000 fps
23	T-3D (7) Cent B-II	46,000	10,000	2000 lbs at 51,000 fps
24	T-3C (7)	38,000	4100	500 lbs at 45,000 fps
25	SIB LS4B	38,000	-	500 lbs at 36,000 fps
				13,000 lbs at 31,000 fps

Table 2-6 (cont')

LAUNCH VEHICLE PERFORMANCE CHARACTERISTICS

		P/L (lbs) at 25,500 fps	P/L (lbs) at 40,000 fps	Additional Data
26	SIB Cent	40,000	9500	1600 lbs at 50,000 fps
27	SIB LS4B Cent	51,000	11,000	2800 lbs at 50,000 fps
				200 lbs at 56,000 fps
28	SIB LS4B CSM	38,000	-	500 lbs at 36,000 fps
				13,000 lbs at 31,000 fps
29	SIC SII LS4B(empty)	250,000	20,500	3000 lbs at 42,000 fps
30	SIC SII LS4B Cent	300,000	70,000	15,000 lbs at 55,000 fps
				8000 lbs at 60,000 fps
31	SIC SII LS4B CSM	289,000	70,000	15,000 lbs at 50,000 fps
				2000 lbs at 54,000 fps
32	SIC (4) LS4B	134,000	16,000	1500 lbs at 44,500 fps
33	SIC (4) LS4B CSM	134,000	16,000	1500 lbs at 44,500 fps
34	120-1 (7)Cent AG-D	165,000	2450	1200 lbs at 44,000 fps
35	120-5 LS4B	88,000	-	10,000 lbs at 35,000 fps
36	120-7 LS4B	105,000	-	11,000 lbs at 35,000 fps
37	120-10 LS4B	150,000	-	18,000 lbs at 35,000 fps
38	156-5 (4) LS4B	180,000	12,000	5000 lbs at 42,000 fps
39	156-5 (4) LS4B S/C	180,000	12,000	5000 lbs at 42,000 fps
40	156-5 (4) Cent	145,000	39,000	7700 lbs at 50,000 fps
41	156-5 (4) R250	65,000	-	40,000 lbs at 27,000 fps
42	R25B R250	65,000	-	40,000 lbs at 27,000 fps
43	MSHT	65,000	-	40,000 lbs at 27,000 fps
44	MSHT Cent	65,000	14,300	1540 lbs at 52,480 fps
45	MSHT Cent Cent (integration in orbit)	65,000	19,800	2200 lbs at 55,760 fps
46	MSHT MSHT Cent Cent (2 launches + integration in orbit)	130,000	35,200	4400 lbs at 55,760 fps
47	MSHT AG-D	65,000	2600	1000 lbs at 43,500 fps
48	MSHT BII	65,000	-	500 lbs at 37,700 fps

adapter weight.

Performance characteristics such as restart capability, manned rating, reusability, spin requirements and diameter constraints, if any, are input to the program in addition to the above payload vs. characteristic velocity data.

2.3.2 Launch Vehicle Related Costs

All costs associated with launch vehicles are presented in Table 2-7 as output from a typical production run. For this run launch facility costs are included in the appropriate stage costs. Existing stages which have been "mothballed" will incur new one-time costs if they are selected for future launches. These costs are indicated in the development column. Data was gathered from a wide variety of sources and modified to provide consistency as to what each cost included. The costs indicated represent most likely estimates which may be used directly in the deterministic form of the model or may be used in conjunction with other data to generate a cost distribution for each category. In the statistical model, the costs presented in Table 2-7 are the modal or most likely costs. These estimates assume that all development programs which have planned completion dates before 1973 are completed as expected.

2.4 COST ESTIMATING UNCERTAINTY

Preliminary research under this study, documented in References 1 & 2, provide an historical analysis of uncertainties associated with cost estimates. This section includes a description of the statistical characteristics of the cost growth factors identified in this analysis and the application of these characteristics to the cost data presented in preceding sections. Selected results from Reference 2 are repeated here for completeness of presentation.

2.4.1 Statistical Characteristics

Over one-hundred high technology programs for the DOD and NASA have been analyzed so that a cost growth factor (ratio of actual cost or best

Table 2-7 Vehicle Related Costs

STAGE COST DATA

	TITLE	FIRST UNIT RECURRING	UNIT INVESTMENT (REUSABLE)	DEVELOPMENT	SUSTAINING	SHARED COST GROUPS			
1)	TAT	1.22		0.0	0.00	19	0	0	0
2)	TAT6	1.4		0.0	0.0	19	0	0	0
3)	SV3A	3.40		0.0	0.0	1	0	0	0
4)	SV3C	3.60		0.0	0.0	1	0	0	0
5)	T-3B	4.91		0.0	0.0	3	8	0	0
6)	T-3D	10.35		0.0	0.0	3	6	0	0
7)	TRAN	6.09		0.0	0.0	3	10	0	0
8)	T3D7	22.00		21.00	0.0	15	3	0	0
9)	T3C7	26.20		26.50	0.0	15	3	0	0
10)	1201	2.75		0.0	0.0	12	0	0	0
11)	1205	13.75		0.0	0.0	12	18	0	0
12)	1200	27.50		0.0	0.0	12	18	20	0
13)	1565	21.20		220.00	20.00	11	0	0	0
14)	S-IB	17.17		95.00	52.6	14	0	0	0
15)	S-IC	54.30		0.0	0.0	14	16	0	0
16)	SIC4	43.00		25.00	0.0	14	16	0	0
17)	S-II	58.00		130.00	87.00	14	22	0	0
18)	S-4B	29.30		60.00	52.00	14	17	0	0
19)	LS4B	14.30		45.00	15.00	13	17	0	0
20)	IMDE	2.60		0.0	8.80	0	0	0	0
21)	AG-D	3.10		0.0	2.60	2	7	0	0
22)	AGLT	3.50		0.0	1.20	2	9	0	0
23)	Cent	6.50		0.0	16.00	4	0	0	0
24)	B-II	0.87		0.0	0.10	5	0	0	0
25)	TE364	0.21		0.0	0.0	0	0	0	0

Table 2-7 Vehicle Related Costs (Cont'd)

STAGE COST DATA (continued)

	TITLE	FIRST UNIT RECURRING	UNIT INVESTMENT (REUSABLE)	DEVELOPMENT	SUSTAINING	SHARED COST GROUPS			
26)	FW4	0.14		0.0	0.0	0	0	0	0
27)	CSM	40.00		150.00	85.00	0	0	0	0
28)	R25B	3.39	169.4	3699.00	244.70	0	0	0	0
29)	R250	2.31	116.1	4739.00	178.20	21	0	0	0
30)	R1.5	6.60	140.0	5578.00	280.00	0	0	0	0
31)	SSTÓ	2.42	144.0	3750.00	284.60	0	0	0	0
32)	S/C	2.00	85.0	1900.00	110.00	0	0	0	0

SHARED COST DATA

	GROUP TITLE	DEVELOPMENT	SUSTAINING
1	ATLS	0.0	4.66
2	AGNA	0.0	2.50
3	TITN	0.0	6.00
4	Cent	0.0	0.0
5	B2S	0.0	0.0
6	T3D	0.0	0.0
7	AGD	0.0	0.0
8	T3B	0.0	0.0
9	AGLT	0.0	0.0
10	TRAN	0.0	0.0
11	156	0.0	0.0
12	120	18.00	4.75

Table 2-7 Vehicle Related Costs (Cont'd)

SHARED COST DATA (continued)

	GROUP TITLE	DEVELOPMENT	SUSTAINING
13	LS4B	0.0	0.0
14	SATN	0.0	110.00
15	TIT7	25.0	0.0
16	SIC	110.0	94.0
17	SIVB	0.0	0.0
18	1205	47.00	0.0
19	THOR	0.0	4.5
20	1200	60.00	0.0
21	R250	0.0	0.0
22	SII	0.0	0.0

Table 2-7 Vehicle Related Costs (Cont'd)

INTEGRATION COST DATA

LOWER GROUP	UPPER GROUP	FIRST UNIT RECURRING	DEVELOPMENT	SUSTAINING
T3D	AGLT	0.0	5.50	0.0
TITN	AGD	0.25	0.0	0.0
CENT	AGD	0.0	3.00	0.0
ATLS	CENT	0.15	0.0	5.00
TITN	CENT	0.0	0.0	2.00
120	CENT	0.0	5.00	0.0
SIVB	CENT	0.0	60.00	2.00
156	LS4B	0.0	80.00	0.0
120	LS4B	0.0	80.00	0.0
156	R250	0.0	50.00	0.0
AGNA	B2S	0.0	2.8	0.0
CENT	B2S	0.0	2.8	0.0
ATLS	B2S	0.39	0.0	0.0
THOR	B2S	0.24	0.0	0.0
T3B	CENT	0.0	2.0	0.0
TIT7	CENT	0.0	6.00	0.0
TIT7	AGNA	0.0	6.00	0.0
ATLS	IMDE	0.0	40.0	0.0
SIVB	CENT	0.0	60.0	2.0
SII	SIVB	6.10	0.0	34.0
SIC	SIVB	0.0	40.0	0.0
T3D	TRAN	1.1	0.0	0.0

current estimate to "planning" estimate) is available for each program. These factors represent actual cost growths from time after original concept definition (basic concept complete). Cost growths during manufacture and testing under contract comprise only a part of the total growth. Thus these ratios do not indicate how effectively initial contract estimates included program uncertainties.

The point in the program at which the initial estimate is taken significantly affects the magnitude of factor numbers. Early estimates tend to be extremely optimistic. These estimates generally are based upon cost estimating relationships which are historically derived, and may cover less than is later understood to be essential. They generally understate the technological difficulty involved in a given enterprise and the cost of many indirect contributors to total program costs-or even to development costs.

The importance of the time of initial estimate is shown by Fig. 2-3, which is presented by Perry from unpublished data collected for the Marshall-Meckling study. The curve plots cost factors for a group of fighter aircraft developed in the 1950's against the time at which the initial estimate was made. The horizontal axis is measured in months before Initial Operating Capability (IOC). The zone designated A is roughly representative of the time at which a Technical Development Plan for fighter aircraft probably would be approved today. Zone B, somewhat higher on the curve, is probably representative of the period during which a production contract emerges or a firm contract target is established. The significant point, of course, is that if observations are taken earlier or later than at A or B, quite different factor numbers will result. The curve itself, although representative of only one lot of fighter aircraft programs, is strikingly like estimating relationship curves derived by Summers, et al, for other kinds of aircraft programs and missile developments during the 1950's. Because the object of the survey presented by Perry was to examine the ability of developers to predict and control program outcomes in the 1960's in comparison to the

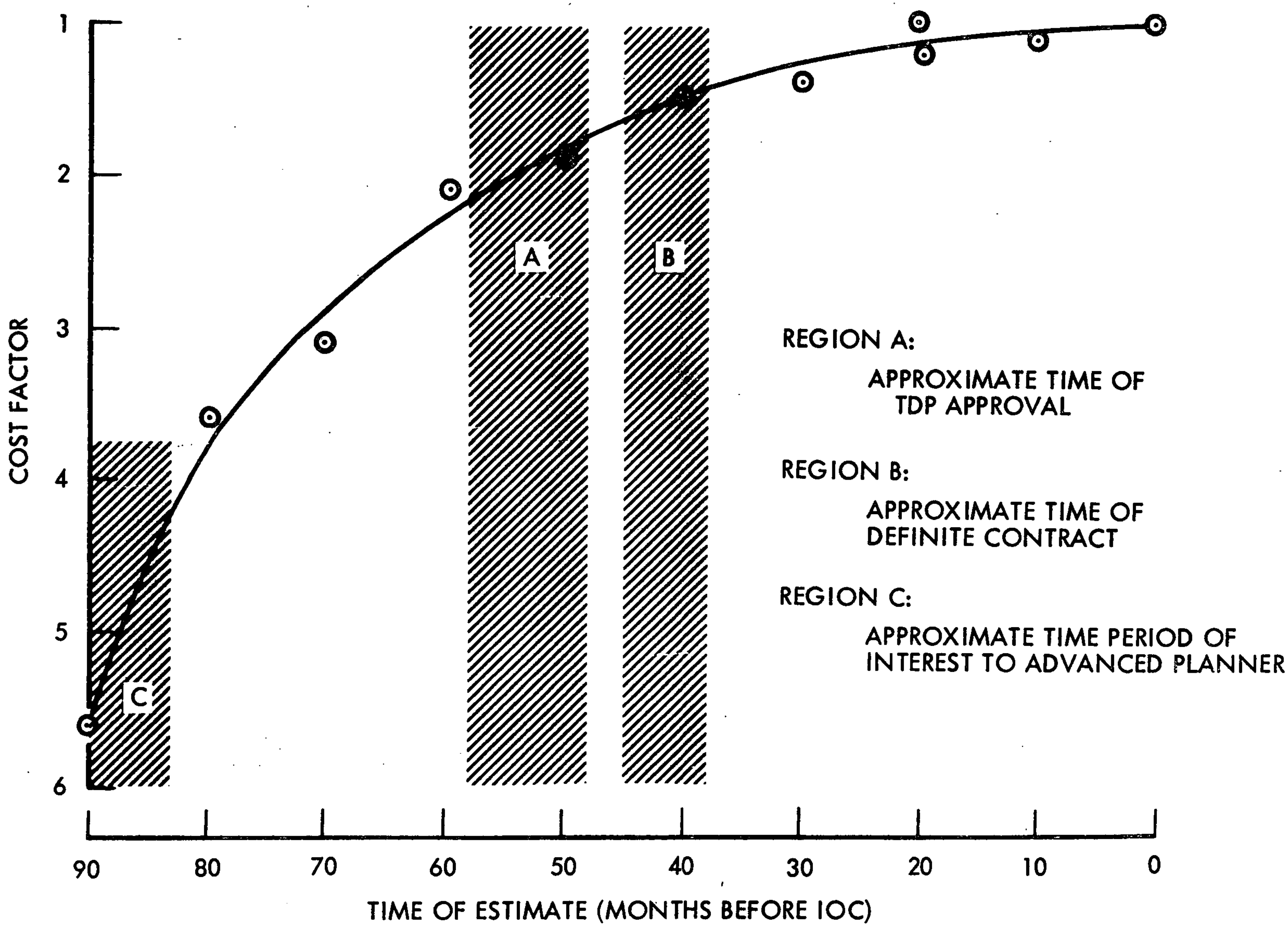

Fig. 2-3 Cost Factors and Time of Initial Estimate

1950's, the bias introduced by taking initial estimates at no definite time in the program was avoided by selecting estimates in Region A whenever available. Region B estimates were used if none were available for Region A. However, the advanced planner who is interested in performing tradeoffs between proposed programs does not have estimates in Regions A or B available for use. He must rely on early estimates available for his analysis. Therefore, whenever possible, the planning estimate was chosen at the time of original concept definition for calculation of the cost factor.

$$\text{Cost Factor} = \frac{\text{final cost or last estimate of final cost}}{\text{planning estimate}}$$

The source of the planning estimate is also important. Each group will have its own ideas on what is essential and how much technological difficulty is involved. The planning estimates used in these cost factors were the agency estimates presented when applying for original funding of the program by Congress. If these estimates were not available, then the contractor's estimate who won the competition was used.

Figure 2-4 shows the cost distributions derived from the 106 systems analyzed. The cost factor for each system was one point in the sample space of an assumed lognormal distribution. The mean, α and the variance, β^2, for each set of data was estimated using maximum likelihood values found by Finney's method modified. The following table indicates the values associated with each lognormal distribution.

Table 2-8

Characteristics of Cost Factor Distribution

	Group	# of Samples	Mean $\hat{\alpha}$	Variance $\hat{\beta}^2$	Mode $\hat{m}$
1	DOD Systems	71	1.8	.76	1.5
2	NASA Propulsive	13	4.3	14.5	1.9
3	NASA Spacecraft	22	2.7	.37	2.5
4	Total	106	2.3	2.4	1.3

The sample data from DOD systems was gathered from published sources which

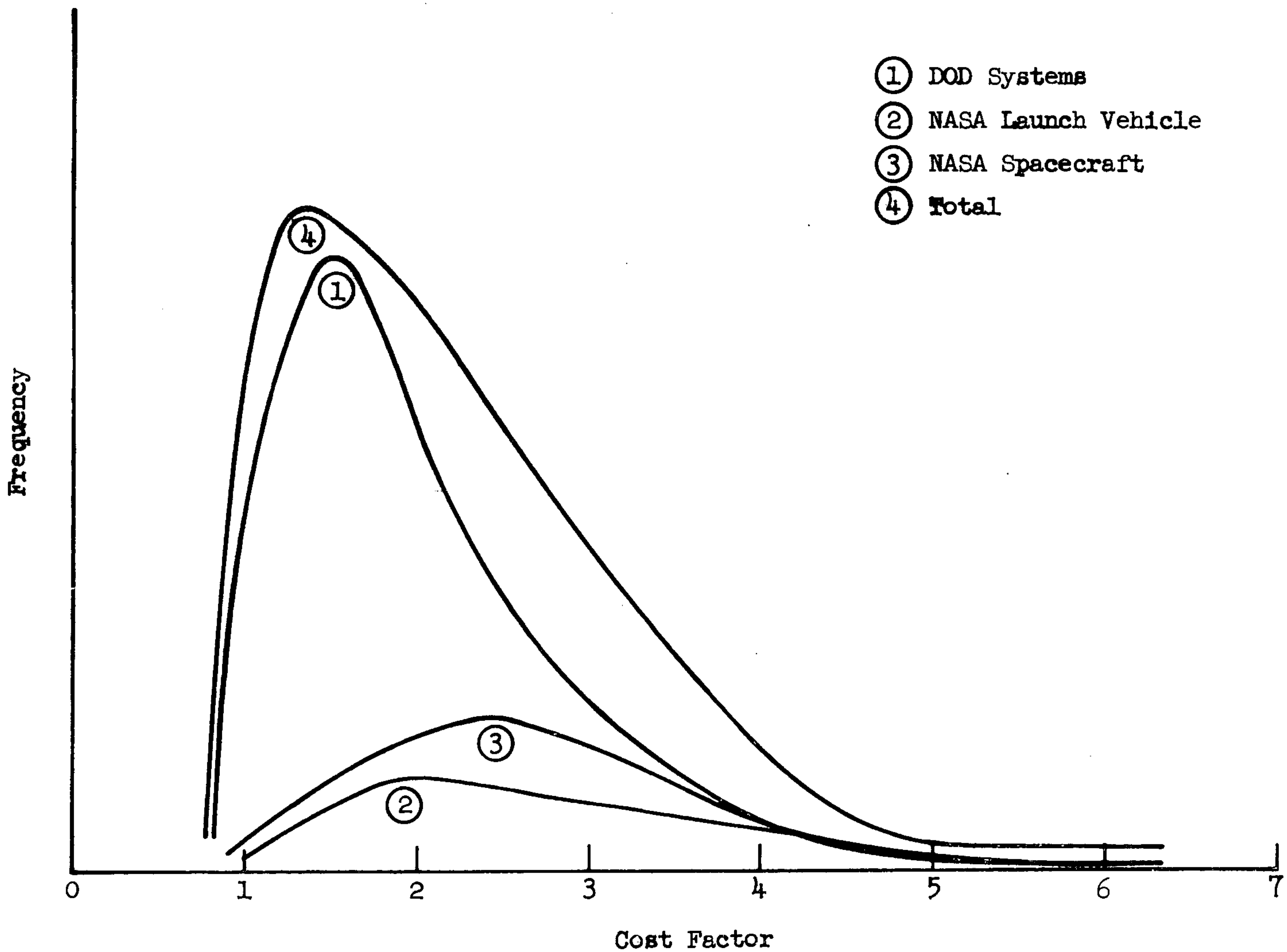

Fig. 2-4 Cost Factor Distribution

quite often included estimates at time of definite contract as a "planning estimate". In other cases the initial estimate was provided with no associated date. In contrast, the NASA growth factors uniformly were based on estimates at time of original concept definition. The differences in distribution characteristics reflect these differences in sample data make-up.

The characteristics associated with these cost factor distributions may be used by the long-range planner as an indication of the magnitude of cost growth which may be anticipated in the future. Since these characteristics are based on historical data they do not predict the future; instead they reflect past performance and indicate what is to be expected in the future under the same guidelines - mainly the technological risks and unknowns which will be encountered.

In sum, the analysis of data has shown that cost growth has occurred in essentially every advance program examined. Even in instances where there was no apparent cost growth, more detailed analysis showed a decrease in number of units procured, a relaxation of original performance or other program modifications to remain within planned cost. An advance planner who wants final actual program costs to reasonably match planned costs can significantly reduce risk and quantify its not-to-exceed cost characteristic by using the statistical cost distribution developed from historical data.

2.4.2 Application of Statistical Analysis

The results presented in the preceding section were applied to the input cost data so output from production runs could be presented in statistical terms. Table 2-9 lists the factor n derived from the cost growth ratios which has been assigned to each launch stage and each type of payload. The factor n is selected so that

$$\text{Prob (actual cost} \geq n \times \text{ estimated cost)} = .25$$

Preliminary runs using these cost factors have shown that the stage-and-one-half concept (or a technology program of comparable risk) and the SSTO + S/C proposed vehicle have such similar cost distributions as to

Table 2-9

COST GROWTH FACTORS

Type of Program	Cost Factor n
Launch Stage	
R 1.5	1.75
R 25 O	1.75
R 25 B	1.75
SSTO	1.6
S/C	1.3
1565	1.4
1200	1.3
LS4B	1.25
CSM	1.1
Existing Stages	1.1
Payload	
Manned	2.0
Planetary	1.7
Science Lab	1.6
UMEO&C	1.3
P&AWOH	1.5
Unplanned	1.6

be indistinguishable at this stage of analysis. Fig. 2-5 shows the total cost distributions for solution A which selects the SSTO + S/C to perform all missions after 1978 and for solution B which selects the R 1.5 to perform these same missions.

In these solutions Mode B $<$ Mode A; however, Mean A $<$ Mean B. The algorithm selects solution A as optimal but cautions that prob (solution B cost $\geq$ solution A cost) = .27. Thus there is not much confidence that solution A will cost less than solution B.

Later production runs have eliminated both the R 1.5 and SSTO concepts. Instead a modified shuttle, MSHT, has been substituted. This shuttle represents any reusable vehicle having similar cost and performance characteristics as the R 1.5 or SSTO + S/C. Conclusions based on use of this modified shuttle will therefore hold for any shuttle with similar risk and performance characteristics.

The historical cost growth ratios were also applied to the reusable vehicle cost estimates available for a 45K lb in polar orbit capability. The ratios for various types of launch vehicles are given below so that prob (launch vehicle development cost $>$ n x development cost estimate) = prob (launch vehicle annual operating cost $>$ n x annual operating cost estimate) = .25.

	Type of Vehicle	Growth Factor n
1)	Fully Expendable 120-10 (7), LS4B, CSM	1.3
2)	Expendable + Winged S/C 156-5 (4), LS4B, S/C	1.5
3)	Expendable + Winged Orbiter 156-5 (4), R250	1.7
4)	Modified Shuttle SSTO + S/C R1.5	1.8
5)	Winged Booster + Winged Orbiter R25B + R250	2.2

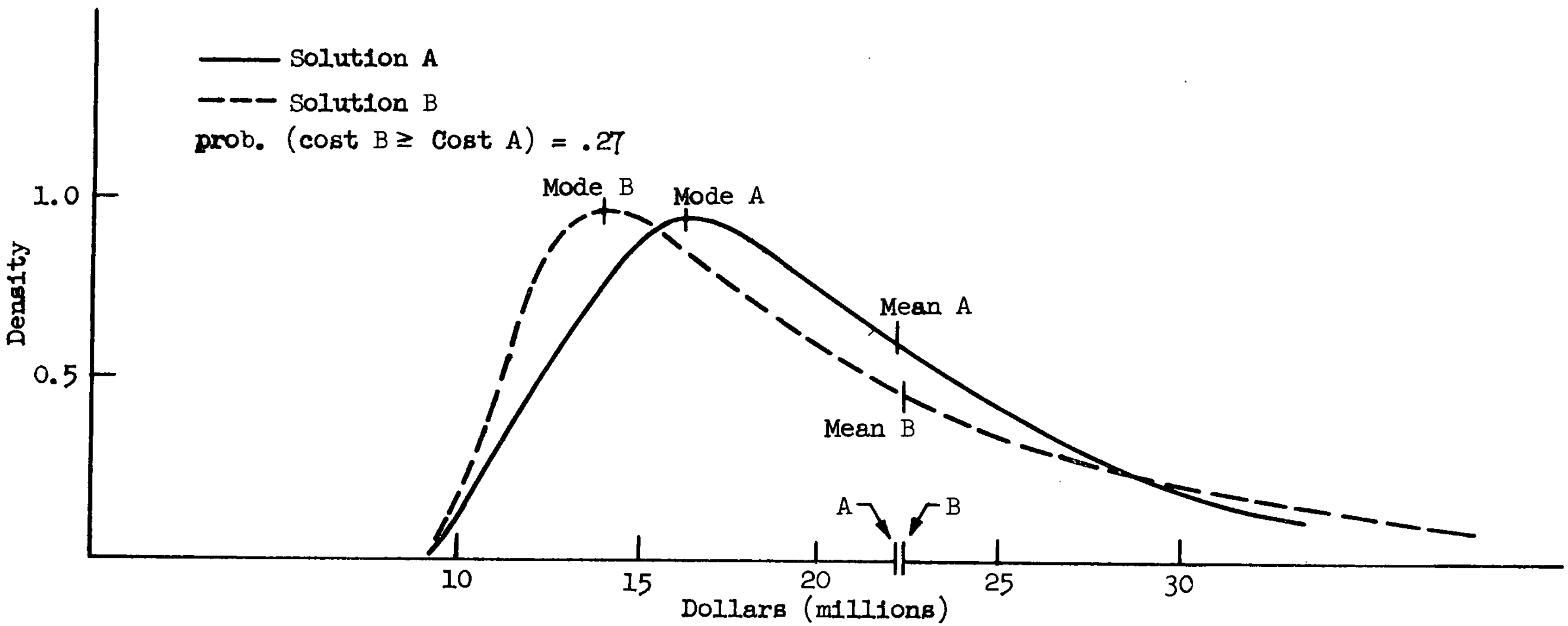

Fig. 2-5 Solution Cost Distributions

Using a lognormal probability distribution which characterizes these cost growth factors, the 50% uncertainty region for each type of vehicle was calculated assuming a .5 correlation between development cost and operating cost for each program. The results are plotted in Figure 2-6 for an average annual launch rate of 50 and a 45-day turnaround time between launches for each vehicle.

Estimated costs were used throughout the production runs as modal or most likely costs. The estimated costs for each vehicle are represented by a point near the lower, left-hand boundary of each closed curve. Actual vehicle costs will fall on or within the closed contours with a probability of 50% or higher. The significant area within these contours indicates that these costs can take on a wide range of values and points up the desirability of analyzing problems with inputs having wide variability on a probabilistic rather than on a single point basis.

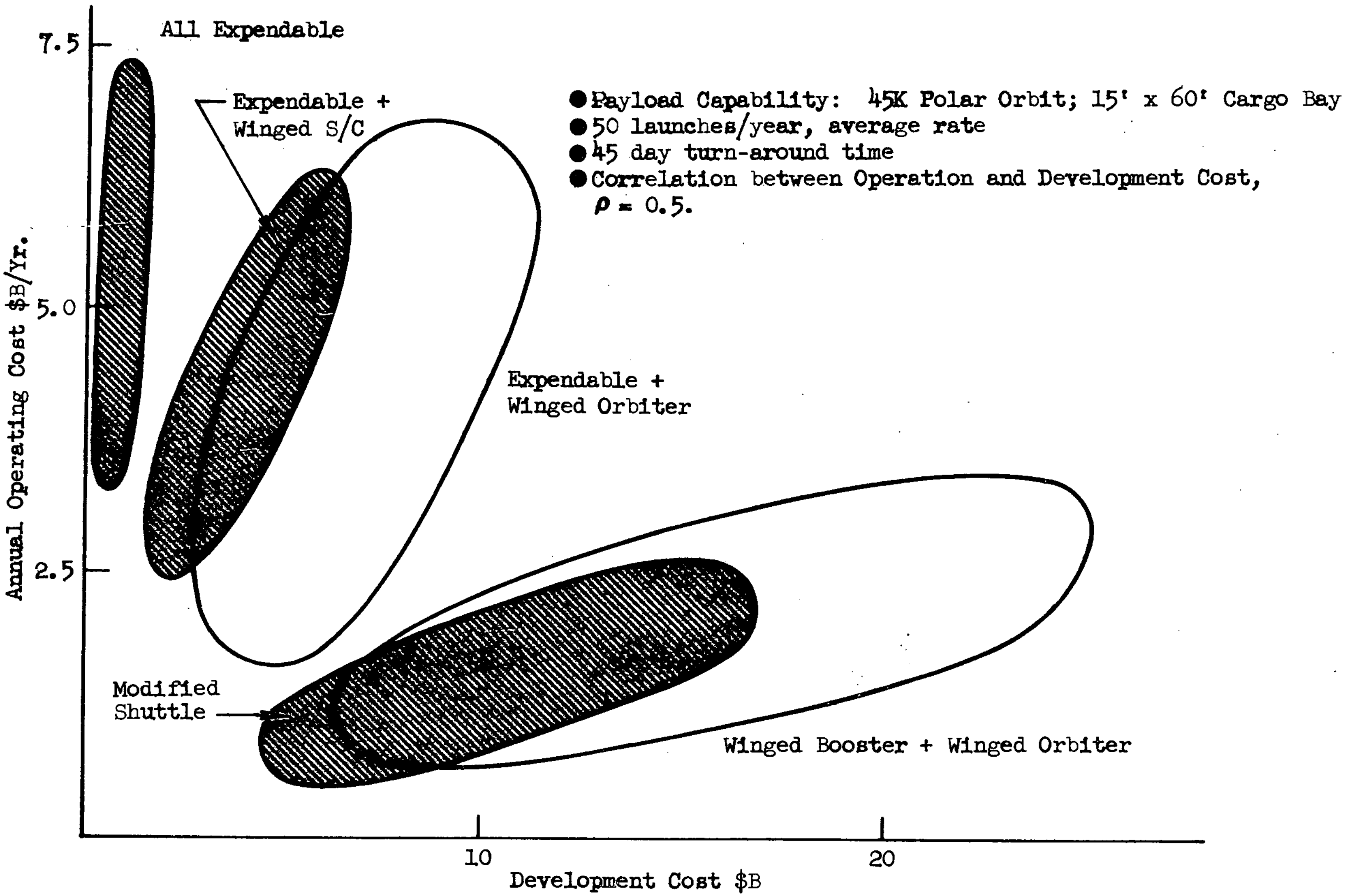

Fig. 2-6 Space Transportation Alternatives: 50% Cost Uncertainty Regions

Section 3

COMPUTER MODEL DESCRIPTION AND OPERATION

The development of a model which compares risks between different programs and estimates the probability of program costs exceeding cost estimates must be based upon historical data. Reference 2 contains a description of the data analyzed and the resulting cost distribution characteristics. Some of this analysis is repeated in this section for completeness. Modifications made during this study to the previous assumptions and their consequences on the output are explained in this section.

The logic for the model is described in this section and is detailed in Appendix C (Vol. 2). Appendix A (Vol. 2) lists the input requirements in detail along with a glossary of input terms. A sample case illustrating the type of probabilistic input and output which may be generated by this model is included in Appendix B (Vol. 2). The sample case may also be used for program checkout. This section indicates the flexibility of the model available through its many options.

3.1 ANALYTICAL APPROACH

The historical analysis described in Reference 2 and in Section 2.4 of this report indicates that the log-normal distribution best characterizes the cost growths to be expected in high-technology programs. While the exponential distribution makes use of the arithmetic mean of the variable, the log-normal distribution makes use of the geometric mean of the variable, or the arithmetic mean of the logarithm of the variable.

If x is a positive variate $(0 \leq \tau < x < \infty)$ and if $y = \ln(x - \tau)$ is normally distributed with mean μ and variance σ^2, then $x - \tau$ is said to be lognormally distributed. The standard (or two parameter) distribution is obtained when $\tau = 0$. In this case the distribution function may be written as

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}} \tag{3.1}$$

where

$$\mu = \overline{\ln x}$$

$$\sigma^2 = \text{var}\ (\ln x)$$

The following relations hold:

$$\begin{aligned} \text{median of } f(x) &= e^{\mu} \\ \text{mean of } f(x) &= e^{\mu+0.5\sigma^2} \\ \text{mode of } f(x) &= e^{\mu-\sigma^2} \end{aligned} \tag{3.2}$$

Thus, one can calculate values for $f(x)$ using standardized normal tables for $f(y = \ln x)$.

3.1.1 Statistical Input

Input is provided basically by two costs for each item instead of the single cost used in the deterministic model. The most likely cost, m, is estimated first, based on the most realistic estimate available. Next a pessimistic cost, b, is estimated such that the probability of exceeding this cost is x% where x, also input, is less than 50. The choice of m and b will determine how skewed the distribution will be.

Using the relationships (3.2) presented in Section 3.1, the input data are developed as follows:

For each cost, two values plus a percentage may be input:

$$\begin{aligned} m &= \text{mode} = e^{\mu-\sigma^2} \\ xx &= x\% \text{ tail such that prob } (Y \geq xx) = x/100 \end{aligned} \tag{3.3}$$

If the cost is certain, then only the value m is input. Y is defined by $N(Y|0,1) = 1 - x/100$, N being the normal cumulative distribution, so we have

$$\sigma(\text{parameter}) = \frac{-Y + [Y^2 + 4\ \ln(\frac{xx}{m})]^{1/2}}{2}$$

$$E(\text{mean}) = me^{3/2\sigma^2} \tag{3.4}$$

$$\beta^2(\text{variance}) = E^2(e^{\sigma^2} - 1)$$

E and σ are stored for each cost since all other variates are functions of these two.

3.1.2 Total Program Characteristics

The algorithm proceeds as before to find a solution based now on expected values for all component costs. Once this solution is found, the appropriate statistical parameters are used to determine the distribution characteristics associated with the total program cost for this solution. If inflation at an average rate p = GRO is input, then the relationship used is

$$m'(\text{in year } Y + N) = (1 + p)^N\ m(\text{in year } Y)$$

$$var'(\text{in year } Y + N) = (1 + p)^{2N}\ var(\text{in year } Y) \tag{3.5}$$

The individual expected values are simply added to determine the total program expected cost

$$E(\text{total cost}) = \sum_i [k_{1_i} + k_{2_i}(1 + p) + k_{3_i}(1 + p)^2 + \ldots + k_{N_i}(1 + p)^{N-1}]E_i \tag{3.6}$$

where

k_{j_i} = number of times cost i is used in year j, $1 \leq j \leq N$

The variance depends upon the interrelationships between variables. All costs associated with each article (stage, family, integration, or launch pad) are interrelated and hence these growth factors are correlated. For example, each cost associated with a stage is distributed lognormally. These costs include

x_1 - Stage hardware recurring or refurbishment

x_2 - ETR launch recurring

x_3 - WTR launch recurring

x_4 - Investment hardware

x_5 - Development hardware

x_6 - Sustaining hardware

x_7 - Sustaining WTR

x_8 - Sustaining ETR

The sum of all these costs is not distributed lognormally; however, the expected value and variance of this sum can easily be determined.

Assume x_j is distributed lognormally $\Lambda(\mu_j, \sigma_j^2)$ with mean E_j and variance β_j^2. The sum $S_n = \sum_{i=1}^{n} x_i$, has expected value $E(S_n) = \sum_{i=1}^{n} E_i$, and in general

$$\mathrm{Var}(S_n) = \sum_{i=1}^{n} \beta_i^2 + 2 \sum_{j<k} \mathrm{cov}(x_j, x_k)$$

where $\mathrm{cov}(x_j, x_k) = E(x_j \cdot x_k) - E_j E_k$.

But if (x_j, x_k) have a multivariate lognormal distribution, then

$$E(x_j \cdot x_k) = e^{\mu_j + \mu_k + 1/2(\sigma_j^2 + \sigma_k^2 + 2\rho_{jk}\sigma_j\sigma_k)},$$

where ρ_{jk} is the correlation of x_j and x_k. Therefore,

$$\mathrm{Var}(S_n) = \sum_{k=1}^{n} E_k^2(e^{\sigma_k^2} - 1) + 2 \sum_{j<k} [E_j E_k (e^{\rho_{jk}\sigma_j\sigma_k} - 1)] . \qquad (3.7)$$

Deterministically, as the estimated value of x_5 increases, the estimated value of x_1 decreases since the planned increase in development cost usually reflects a corresponding increase in the state of the art which produces lower operating costs.

Statistically, however, the cost growth of x_1 is directly correlated to the cost growth of x_5 since the most important influence on cost growth is unplanned weight increase which causes all costs associated with a particular stage to increase. Thus for a particular stage, ρ_{jk} is non-negative for all associated costs. A similar analysis holds for shared and integration articles which involve fewer cost types.

Theoretically, if ρ_{jk} were known for all appropriate j and k, then $\mathrm{Var}(S_n)$ could be determined using (3.7). Unfortunately, cost data are not available for past programs in enough detail to allow such a determination. Twelve completed high technology programs did have costs broken down into two categories - development and production. An analysis of these costs resulted in an estimate of .29 for the correlation between development and operating costs. Considering the small number of programs in the sample, this estimate for ρ_o agrees well with the the .5 correlation heuristically expected. The computer program uses this one input correlation factor between development and operating costs to determine the variance of the sum. All other correlations are assumed to be zero (as between groups x_2 and x_3), or one (as between elements within each group, e.g., hardware sustaining costs for one year are directly correlated to these same costs for the following year).

The variance associated with the total program cost, is therefore realistically determined by the following equation:

$$\mathrm{Var(total\ cost)} = \sum_i [k_{1_i} + k_{2_i}(1+p) + k_{3_i}(1+p)^2 + \ldots + k_{N_i}(1+p)^{N-1}]^2 E_i^2(e^{\sigma_i^2} - 1) + 2\sum_j [E_{j1} E_{j2}(e^{\rho_o \sigma_1 \sigma_2} - 1)] \tag{3.8}$$

where

E_{j1} = the expected operating cost associated with some article j

E_{j2} = the expected development cost associated with same article j

σ_1, σ_2 = the corresponding lognormal parameters and ρ_0 is the input correlation between development and operating costs.

The algorithm continues to find solutions, whose total expected costs are placed in ascending order, until n solutions have been found where n = NSOL is an input variable. As each solution is found, the corresponding assignment is printed out along with information concerning its total cost distribution and its relation to other solutions found previously.

3.1.3 Solution Comparisons

The analyst will be attempting to select a fleet of launch vehicles and associated program elements to accomplish a proposed set of missions from alternative combinations. He will want to determine the margin of cost difference between alternative choices. A wide variety of output is available from the algorithm since, for each solution, the total distribution with its associated parameters is known. Equations (3.6) and (3.8) define the expected value and the variance of each total program cost. The parameters, σ, μ, for each such assignment may then be found using

$$\frac{\mathrm{Var(TC)}}{[\mathrm{E(TC)}]^2} = e^{\sigma^2} - 1 \qquad (3.9)$$

and

$$\mu = \ln[\mathrm{E(TC)}] - \frac{\sigma^2}{2} \ .$$

The most likely value, m, for each assignment is determined by

$$m = \mathrm{mode} = \mathrm{E(TC)}(e^{-3/2\sigma^2}) \qquad (3.10)$$

The probability that the total cost will not exceed some value Y may be found from the following relationship:

$$\mathrm{prob}(X \leq Y) = p \quad \text{which is equivalent to} \quad N(Z|0,1) = p \qquad (3.11)$$

where

$$Y = e^{(\sigma Z + \mu)} \ .$$

The scientific subroutines NDTRI and NDTR can be used to find Z given p or p given Y, respectively. Using the above relationships, the probability that the expected program value (mean) will exceed the estimated value (mode) is determined.

To compare two assignments, the probability that one assignment will actually cost more than the other should be known. The log-normal distribution allows such a determination providing that the degree of correlation between programs is provided. Thus, two assignments involving different development programs may be highly correlated if each development program involves the same type of risk, or they may be only slightly correlated if one involves a large new development and the other utilizes existing technology to accomplish the same mission profile.

Two assignments with total costs C_A and C_B distributed log-normally will have parameters $[V(TC_A), E(TC_A)]$ and $[V(TC_B), E(TC_B)]$ determined by Eqs. (3.6) and (3.8). The parameters (μ_A, σ_A) and (μ_B, σ_B) may be determined by Eq. (3.9). Then $\log C_B/C_A = \log C_B - \log C_A$ is normally distributed with mean $= \mu_B - \mu_A$ and variance $= \sigma_A^2 + \sigma_B^2 - 2\rho\ \sigma_A\ \sigma_B$ where ρ is the correlation coefficient, discussed in the paragraph above, which describes the relationship between assignments C_A and C_B.

Thus the probability that assignment B will cost less than assignment A is

$$PR\left(\frac{C_B}{C_A} < 1 \middle| \frac{\mu_B}{\mu_A} = k \text{ and } \rho \text{ given}\right) = PR\left(\ln \frac{C_B}{C_A} < 0\right)$$

$$= N(0 | \mu_B - \mu_A = \text{mean and } \sigma_A^2 + \sigma_B^2 - 2\rho\ \sigma_A\ \sigma_B = \text{variance}) \qquad (3.12)$$

$$= N\left[\frac{\mu_A - \mu_B}{(\sigma_A^2 + \sigma_B^2 - 2\rho\ \sigma_A\ \sigma_B)^{1/2}} \middle| 0,1\right] \quad \text{for} \quad \rho < 1$$

The probability expressed in Eq. (3.12) is output for representative values of ρ for all pairs of assignments of interest so the analyst may obtain insight into the interrelationships between the assignments. For example, the analyst may find that one assignment produces a low model value for total program cost, but the uncertainty associated with this assignment is so large that a much higher expected value results. A second solution may have almost no associated uncertainty so the modal and expected value are nearly the same. In some cases the more certain solution, although it has higher modal value than the first solution, would be preferred.

3.1.4 Three-Parameter Lognormal Distribution

The standard lognormal distribution may be defined by its mean and variance. In initial test cases, this lognormal distribution describing the total launch vehicle cost resulted in a typical curve shown in Fig. 3-1 by the solid line. The probability of the total cost being less than the modal or most likely estimate varied from .2 to .35. This computed probability is unrealististically high based upon historical data. Therefore the model was modified to include the three-parameter lognormal distribution. The third parameter of this distribution is the point τ such that prob $(x \leq \tau) = 0$. If $\tau = 0$ then the standard two-parameter family is generated. Using historical factors, τ was chosen as one-half the modal value for each entering cost. Each cost distribution is then obtained as before using the variable $x - \tau$ instead of x in the appropriate formulas. The parameter τ for the total cost distribution is a function of all corresponding third parameters for each component cost. The resulting value of τ is approximately one-half the calculated modal value. Once τ has been calculated for the optimal assignment. it is used for suboptimal solutions also. Thus direct comparisons between solutions are calculated exactly as described in Section 3.1.3.

Using the 3-point lognormal, the probability that the total cost would be less than the modal value ranged from .08 to .16 which is the expected result from historical growth factors. Fig. 3-1 shows the same data analyzed assuming the 2-point and 3-point lognormal distribution. The 3-point distribution follows closely the expected cost distribution based on historical data and consequently will produce better statistical comparisons than the two-parameter distribution.

3.2 LOGIC

The optimum assignment program is integrated with the budget smoothing program through use of a master program which translates from one model to the other. The deterministic budget smoothing program was developed

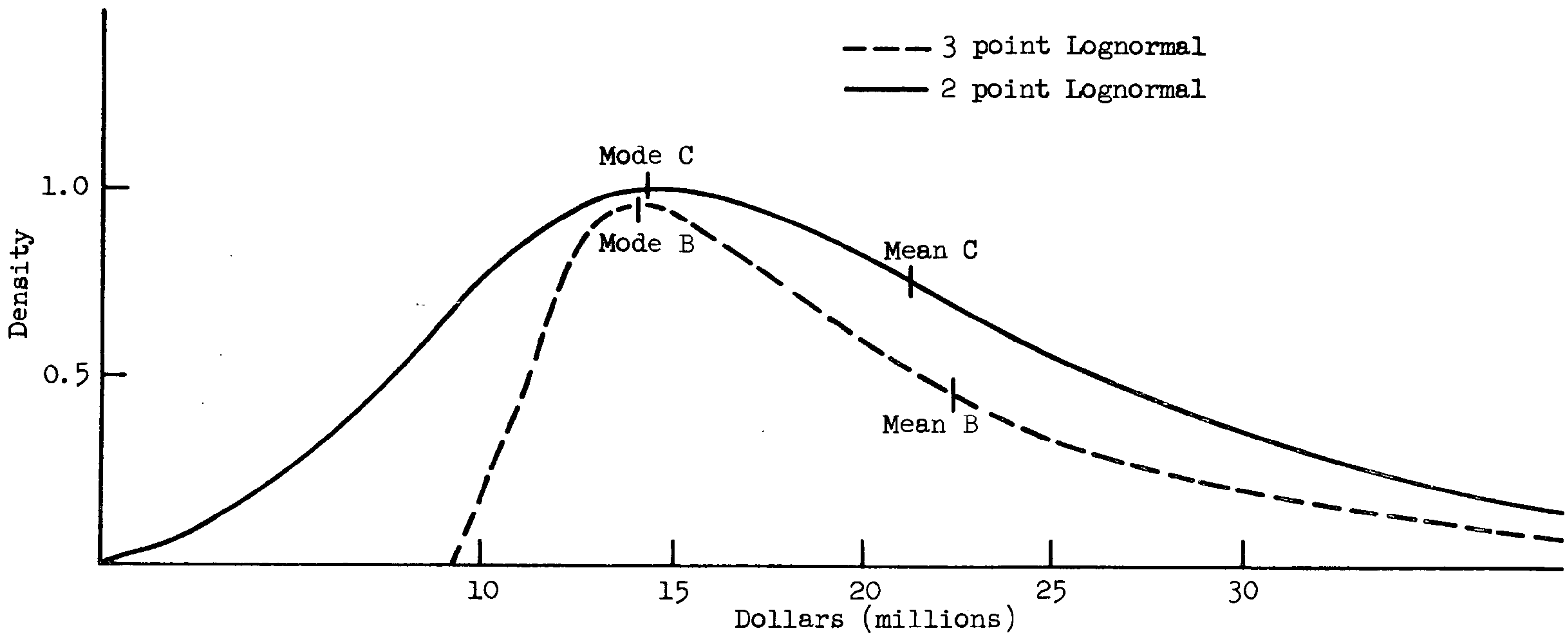

Fig. 3-1 Distribution Characteristics

by R. E. Slye, the Technical Monitor for the study, and has been described in Ref. 1. This smoothing program was extended to handle probabilistic input and to output budget levels showing inherent cost uncertainties. It is therefore further discussed in this volume. A general logic diagram of the master program and the two main subroutines, ASSIGN and SMOOTH, are presented in Figs. 3-2 through 3-4.

The master program (MASTER) calls first the vehicle assignment program (ASSIGN) in order to obtain mission data, cost data, and optimum vehicle-to-mission assignment based on these data. Input data are output using both modal and expected values if appropriate. The N best solutions based on expected costs are output along with their statistical relationships, but only the optimal assignment is saved for use by MASTER. MASTER then transforms these data from the optimal assignment so that they may be used directly by the budget smoothing program (SMOOTH). SMOOTH shifts development dates, launch dates and development duration to achieve a level of spending close to the desired level. The desired levels of spending and constraints on possible program shifts are input to SMOOTH directly. Annual spending levels are output by SMOOTH based on expected costs and most likely costs. A 50% confidence interval about the expected cost is output and displayed on each plot of annual spending levels.

The new development dates and development costs generated by SMOOTH are transformed by MASTER so that ASSIGN can use the data for a revised vehicle to mission assignment. The program iterates between ASSIGN and SMOOTH until no major changes are generated by SMOOTH. Then MASTER either terminates or starts a new case with associated data.

Figure 3-5 illustrates the overall relationship between the 32 subroutines. Subroutines INPUT and PLOT are available to all NASA computer users and are described in Appendix C. Subroutines PACK and AFRMT were written in 360 Assembler Language by R. E. Slye, the Technical Monitor of this study. Listings for each are included in Appendix D and a description of both

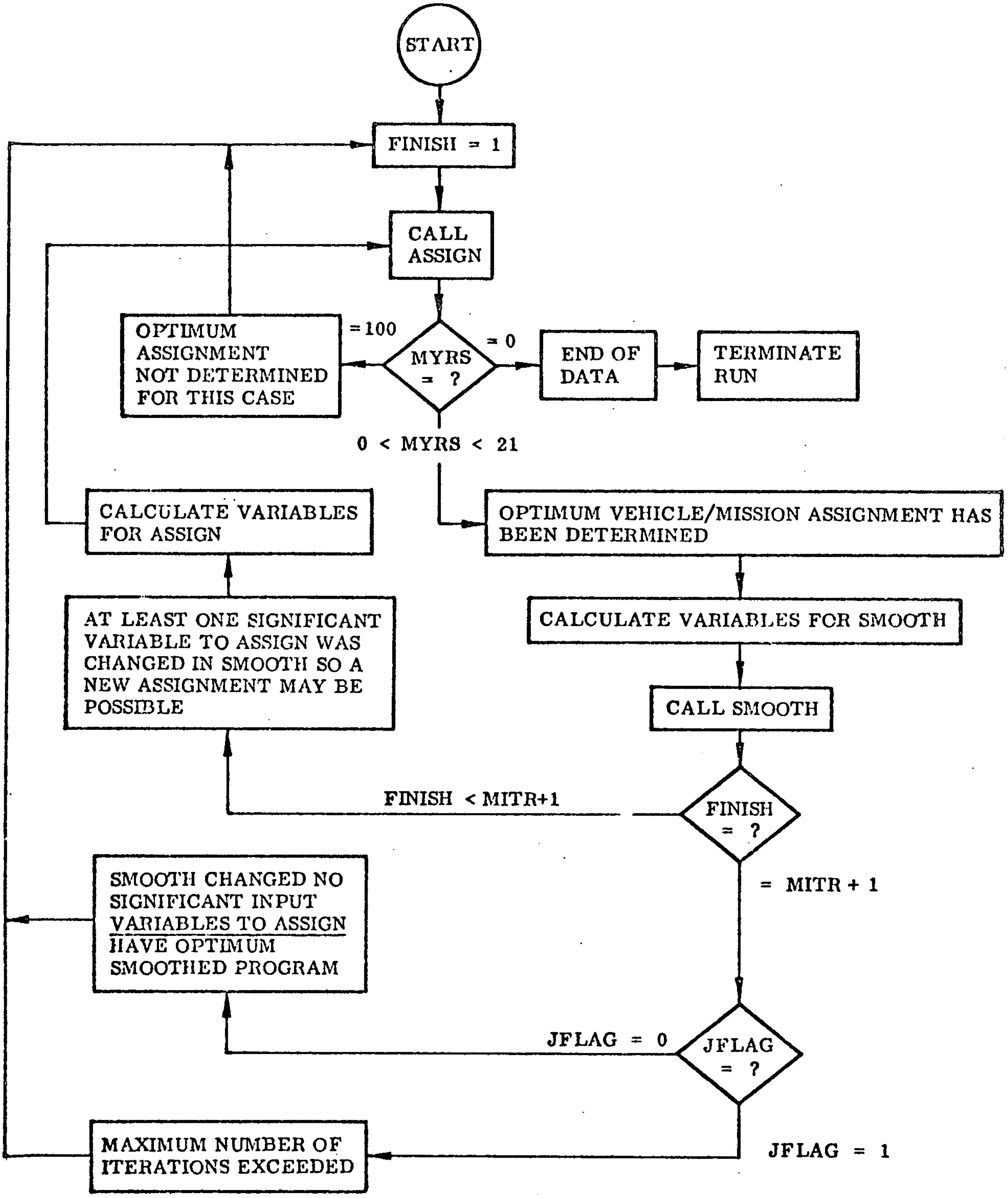

Fig. 3-2 General Flow Diagram for MASTER Program

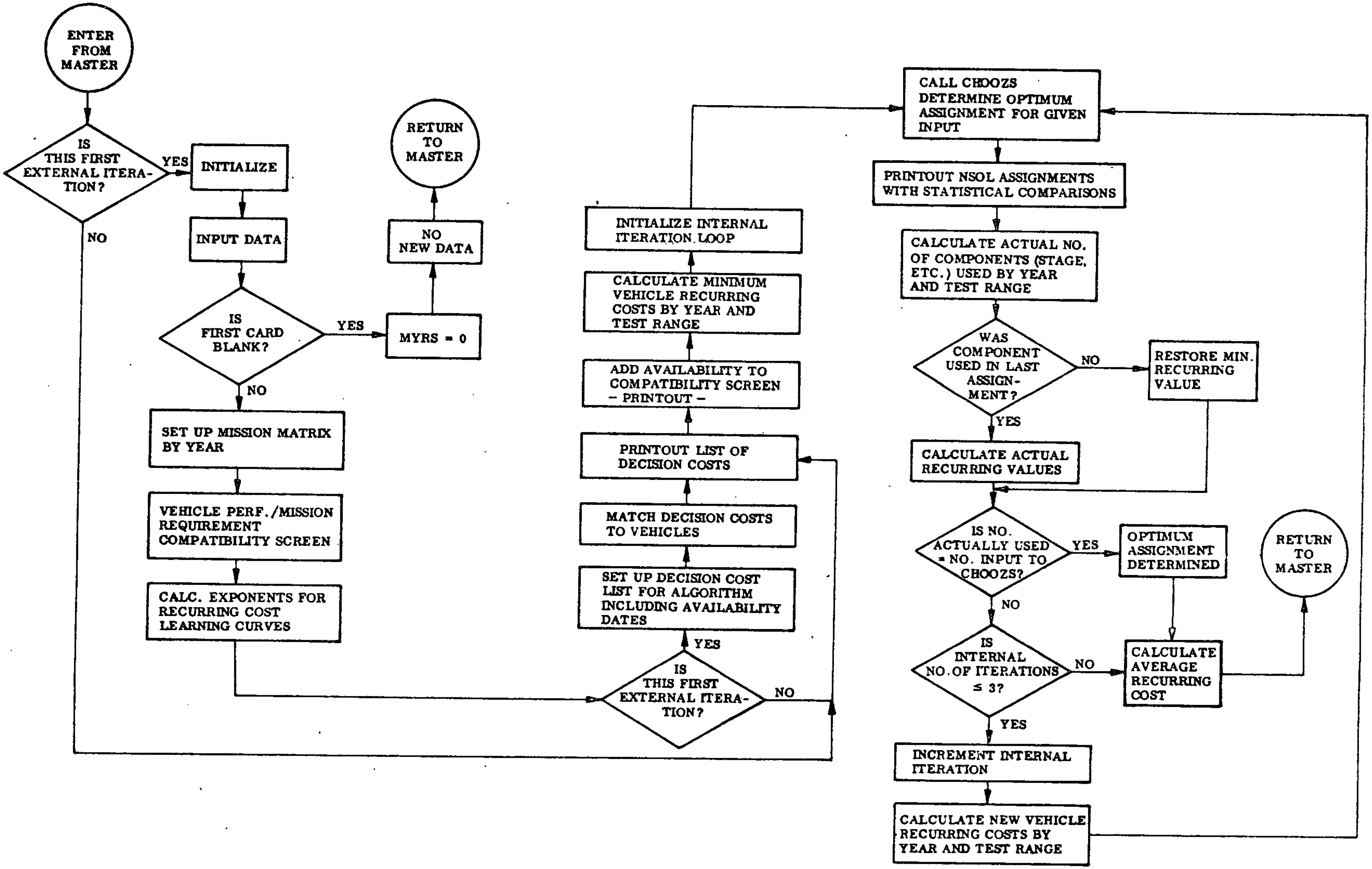

Fig. 3-3 General Flow Diagram for ASSIGN Program

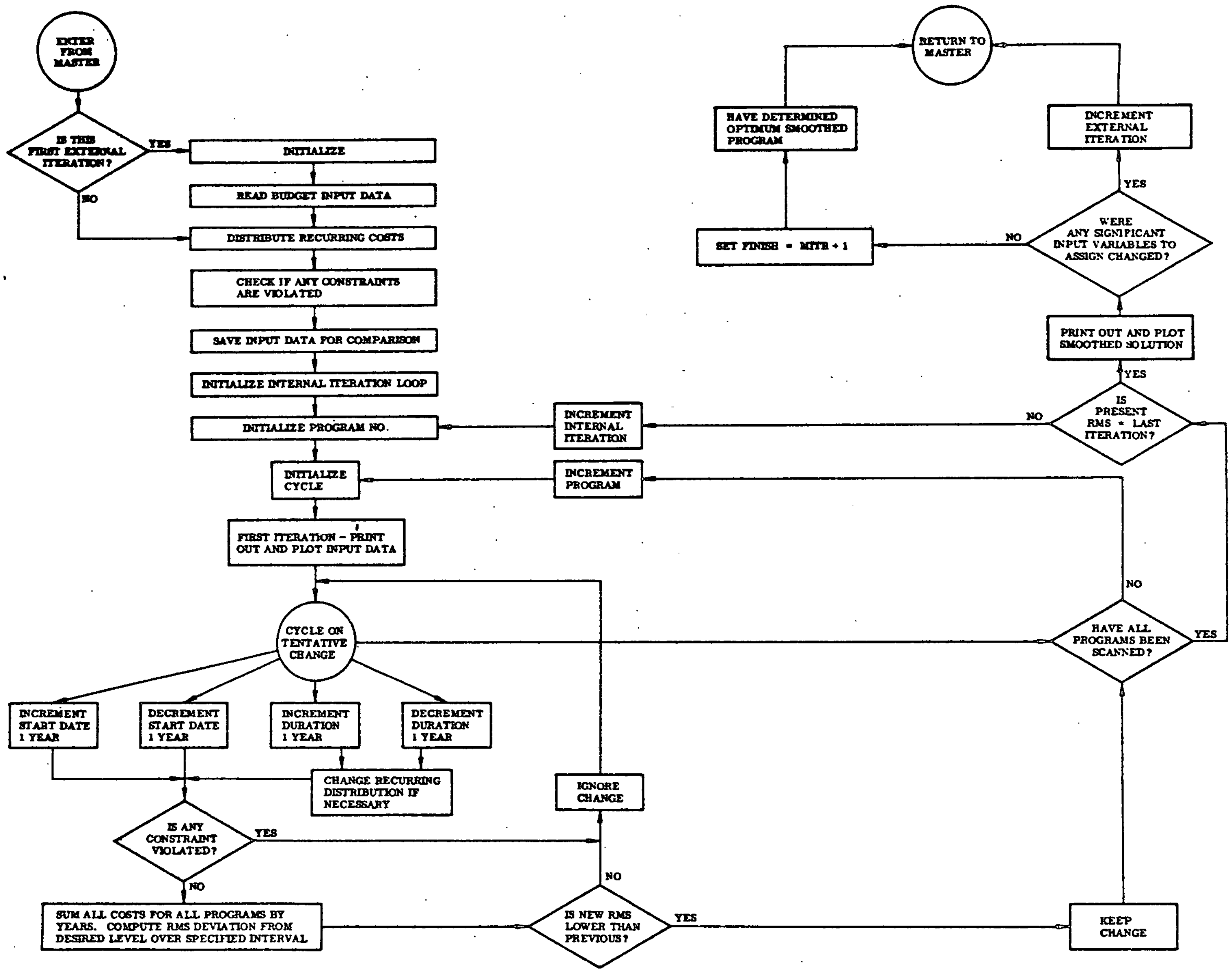

Fig. 3-4 General Flow Diagram for SMOOTH Program

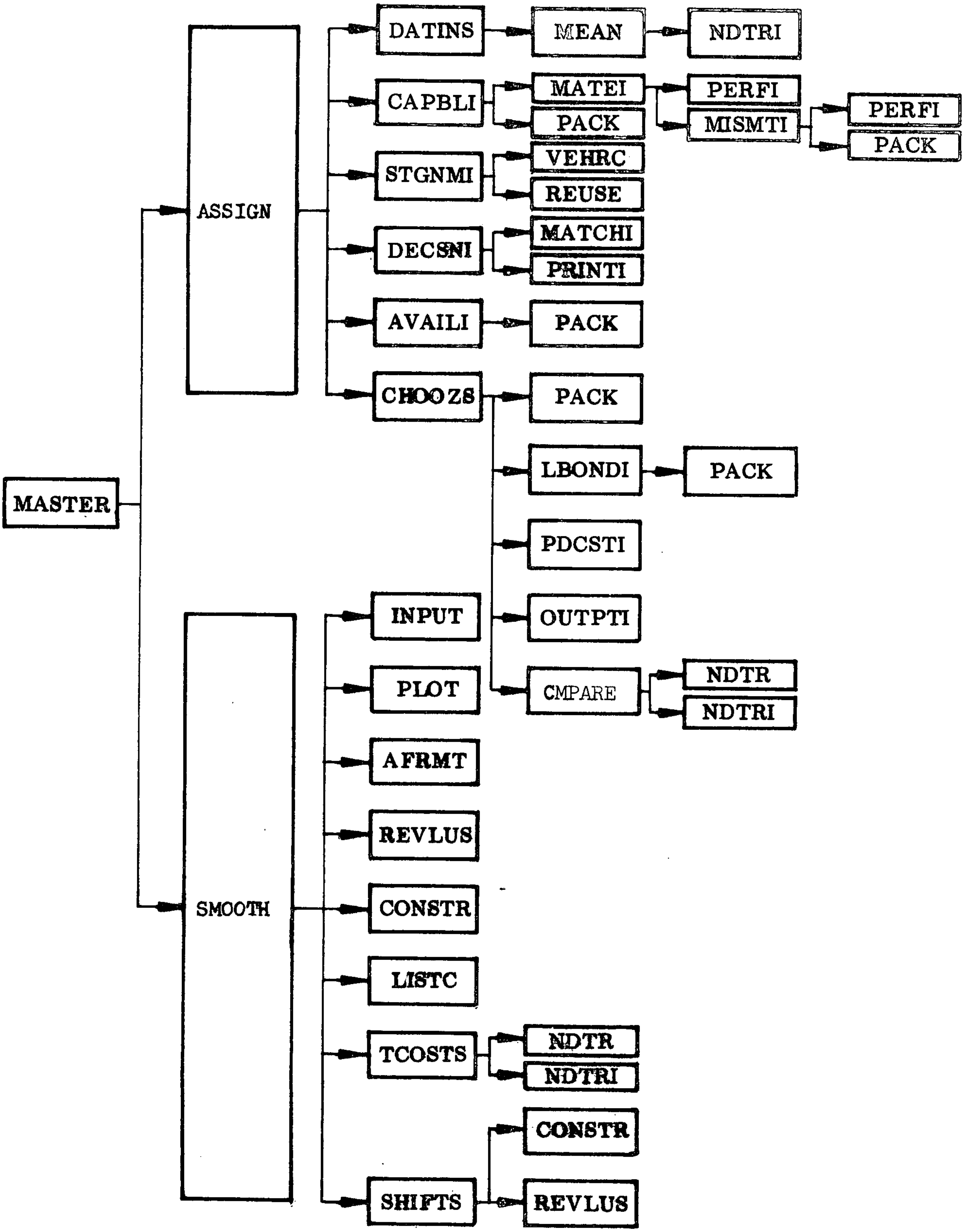

Fig. 3-5 Program Subroutine Relationships

subroutines appear in Appendix C. The remaining subroutines have flow charts in detail in Appendix C and Fortran listings in Appendix D. The first comment card in each subroutine listing states the primary purpose of that subroutine. Other comment cards describing the purpose of each section and defining any pertinent variable whose name is not mnemonic are distributed liberally throughout the listing so that new users may familiarize themselves with the logical function of each subsection within the program.

Dimension restrictions are detailed in Appendix A for input variables and for internal variables indirectly associated with the input. All other dimension constraints, data statements, and equivalence relations may be found at the beginning of the program listing for MASTER in Appendix D.

Each subroutine has been constructed as a self-contained package with a minimum of interrelationship between routines. Consequently, any subroutine can be altered, expanded, or modified with the minimum amount of effort. The length of each subroutine was restricted so that maximum use of the Fortran H mode of compilation would result. This efficient mode of compilation results in reduced storage and reduced run times in comparison with the more common Fortran G mode.

3.3 PROGRAM OPTIONS

The options available to the analyst are of two types: (1) automatically determined by the program from the data input and (2) specified directly by the user. In general, cost data may be input as a most likely value (modal value) for each type, plus an xx% tail value for each type, where xx is an input value. If xx is input as zero for any cost, then the model interprets that cost as being certain so the modal value for that cost equals the expected value. If xx is zero for all cost data input (i.e., there are no upper tail values given), then the program bypasses all statistical calculations. In this manner the deterministic model was embedded into the present probabilistic model through use of a type 1 default option.

Rate effects on recurring costs are also ignored if no learning curve percentages are input. Other default options include the automatic distribution of launch vehicle recurring costs unless overridden by input to the variable ALPI, the automatic input of zero to most applicable budget items unless overridden by actual input, and the automatic use of the extension and acceleration options in the smoothing section unless FALSE is specified for the variables EXT or ACCL respectively. If NSOL (the number of solutions to be output in ascending order of total program cost), is input as zero, one optimal solution will still be found.

There are five major options which must be specified by the user - LP, MOS NOPT, NU, AND NCSTR.

3.3.1 LP Option

The first such option is the code for logic printout. In a test run code LP = 2 should be used so that the internal logic may be checked for accuracy. Many lines of output are required, however, so this value should not be used in general. If LP = 1, suboptimal solutions may be traced in the branch and bound logic and the optimal solution justified step by step. Thus, reasons for selection or non-selection of a program element in an assignment may be determined in detail if desired. LP = 0 is the normal mode for production runs. Only final solutions and characteristics of these solutions are output under this last mode.

3.3.2 MOS Option

In order to accomodate some of the various uses which the analyst may have for the model, four alternatives are made available to the user. On the first data card, the user specifies which mode he desires by an appropriate value for MOS (method of solution).

MOS = 0 Optimize launch vehicle assignment and smooth the resulting budget within constraints input to SMOOTH

MOS = 1 Input specific launch vehicle assignment and smooth the resulting budget

MOS = 2 Optimize launch vehicle assignment and output associated costs by year and program (do not smooth budget)

MOS = 3 Input specific launch vehicle assignment and print out associated costs by year and program

Thus the optimal assignment program without smoothing is available using MOS = 2, the smoothing program alone using MOS = 1 and the integrated program using MOS = 0. MOS = 3 is useful in testing assignments derived from outside sources. Total cost distributions are then available for these assignments which may be compared to previously found optimal assignments.

3.3.3 NOPT Option

The mission/vehicle compatibility screen may be in one of three forms. The basic screen (NOPT = 1) consists of first looking to see if there is an a priori vehicle assignment. If there is one, all other vehicles are excluded from consideration for that mission.

If there is no such pre-assignment, the payload capability of the vehicle is compared to the payload desired for each mission at the required characteristic velocity. Modularization is taken into consideration in determining whether the launch vehicle can or cannot accomplish the mission. The availability of each vehicle for a particular mission is determined later in subroutine AVAILI, where a final compatibility matrix is output.

If NOPT = 2 is specified, the basic screen above is applied to any vehicle input directly and to all vehicles formed in the stage-matching screen performed in subroutine MATEI.

If NOPT = 3 is specified, the basic screen is augmented by tests on the stabilization, man-rating and other requirements input on the mission card. If NOPT is not specified as 2 or 3, then the basic screen is the default option.

3.3.4 NU Option

NU, the number of reusable units to be purchased, is zero if the stage is expendable. However, if the stage is reusable then either a positive number is input to NU and this number is used directly by the program throughout all iterations, or a negative number is input to NU and then the program uses this estimate for the first iteration but calculates its own estimate based on actual usage for succeeding estimates. The program estimate is based on turn-around-time, amortization lifetime, and mission use time, as appropriate. The estimate is calculated in subroutine REUSE (the logic flow diagram is in Appendix C, Vol. 2).

3.3.5 NCSTR Option

NCSTR, the number of budget constraints input to subroutine SMOOTH, must be specified. If NCSTR = 0, this external constraining option is by-passed.

Constraints are input directly to SMOOTH for missions and for miscellaneous programs having no associated launches. They are keyed according to the following table where:

KODE = the type of constraint by key number (see Table 3-1)
NPROG = N = the constrained program reference number
KPROG = K = the constraining program reference number
CS = associated real number constant

Input program data must satisfy the input constraints to ensure a correct output from SMOOTH. Any violations in input data are printed out before "smoothing" begins so that the user is aware of the condition. The program will continue even if violations occur since in many cases the violations are corrected by the "shifting" process.

Costs associated with launch vehicles in the optimal solution are automatically constrained in MASTER. KODE 11 is used to ensure that all launch vehicle development programs selected by ASSIGN in the optimal

Table 3-1

KEY TO PROGRAM CONSTRAINTS[a]

KODE	
1	$START_N > END_K + CS$
2	$END_N + CS < START_K$
3	$START_N = CS$
4	$END_N = CS$
5	$DEV.\ DURATION_N = CS$ (FIXED DURATION)
6	$LAUNCH\ DATE_N + CS \leq LAUNCH\ DATE_K$
7	$LAUNCH\ DATE_N \leq CS$
8	NO CHANGES ALLOWED
9	$START_N \geq CS$
10	$LAUNCH\ DATE_N \geq CS$
11	$END_N + CS < LAUNCH\ DATE_K$

(a) START and END refer to development

solution end before the associated payload is to be launched. Thus, SMOOTH is automatically constrained so that the optimal vehicle assignment input to SMOOTH is still a feasible candidate assignment after SMOOTH is complete. Whether the assignment input to SMOOTH remains optimal or not depends on which variables have been "shifted" by SMOOTH. If key variables have been changed, ASSIGN is called to again determine the optimal assignment. Depending on the effect of the "shift" changes, this new optimal assignment can be the same as the previous assignment or it can be different.

Other options such as using the Beta distribution or an alternative input distribution for any development cost are explained in the comment section of Appendix A (Vol. 2) Input Requirements.

3.4 GENERAL OUTPUT

First, all the input data are output for reference, including data computed by the program which will be input to the ASSIGN algorithm. Both input modal values and computed expected values are output whenever appropriate. Then the optimal assignment is output listing each mission and the assigned optimal vehicle, along with total mission model cost. If NSOL is greater than one, each assignment in ascending order of expected total cost is output until NSOL solutions have been found. For each assignment, the log-normal distribution describing the uncertainties associated with its total cost is output along with its modal (most likely) value and 50% uncertainty interval. Each assignment is compared to each preceding one in order to determine the probability that it will cost more than the one preceding, given a definite correlation between assignments.

Input to SMOOTH is output automatically as it appears on the data card. "Average" recurring cost data for each vehicle in the optimal assignment is computed in VEHRC. This cost is determined by totaling the actual recurring costs of all program elements associated with each vehicle over the entire mission duration and then dividing by the total number of vehicles used throughout the mission model. The constraints input to the program and those calculated in MASTER are output for reference. Any violations to these constraints in the input data are noted. Finally the cost data comprising the optimal assignment that is input to SMOOTH is output by program and type and also by year. A plot showing expected spending by year and desired spending level by year follows. The most likely (modal) spending level by year and the upper bound on a 50% confidence interval are also included on the plot.

The program then smooths this input data and outputs the final result in the same form as it did the input data. Launch vehicle requirements by year are output using the smoothed data. At this point the program either terminates because an optimal smoothed assignment has been found or else it returns to ASSIGN and outputs the new data which will be used in the algorithm. The output cycle then continues as explained above until an optimal solution has been found.

The output from this model can be applied to a wide range of space program evaluations:

- To macro-problems that evaluate various options of total space programs such as that presented in section 4,
- To intermediate problems that analyze separate portions of a space program such as optimizing a scientific, exploratory, service satellite program within a total space program,
- To micro-problems such as determining the cost optimal subsystem among several alternatives for a given space vehicle,
- To provide economic analysis of new space program directions.

In this last use of the model, as indicated in section 5, an integrated total national space program, including on-going and presently planned missions plus potential new space concepts, is evaluated and the decision maker is provided with quantified data that reflects fuller utilization of the national space program plant in making new space concept decisions. These decisions can be based on all significant space program elements, including their complex interdependence.

In addition to its primary application to the space program in this study, by changing parameters and certain analytics the computer model can also be applied to a broad range of optimal resource allocation problems in areas other than space.

In all applications the capability to quantitatively evaluate the uncertainties known to be present in advanced program costs provides the user with a unique evaluation tool.

Section 4

EXERCISE DEVELOPED MODEL

Both the deterministic and statistical models were used in production runs. Historical data on appropriation levels, base costs, mission types and traffic rates, and launch vehicle performance, included in Section 2, were used as a basis for these runs. A series of production runs over a range of budget options are described in this section. Graphics aid in the analyses of output from these runs. The evaluations and results included in this section are typical of the many applications of this assignment model in analyzing and formulating advanced mission plans. Selected methods of presentation which may be of use to the space program evaluator are included.

4.1 PROGRAM LEVEL WITHIN BUDGET

The mission profiles presented in section 2.2 were input to the model with each of the three selected appropriation levels. The resulting program in each case was smoothed to reflect available resources. Funding distributions for the various programs within the envelope of the total space program are presented in Figures 4-1 through 4-5 for each level of appropriation under consideration. Both modal and expected values were used as input for comparison. The authorized missions are designated as "Run Out" on these figures.

Based on input data provided in Section 2 of this report the following selected observations are typical of output available from this model: (1) the modified shuttle is selected as the optimal vehicle for all manned missions after it is available, (2) Budget Level #3 will support only unmanned missions, so no shuttle is developed, and (3) by postponing unmanned flights scheduled to occur in the late 1970s,

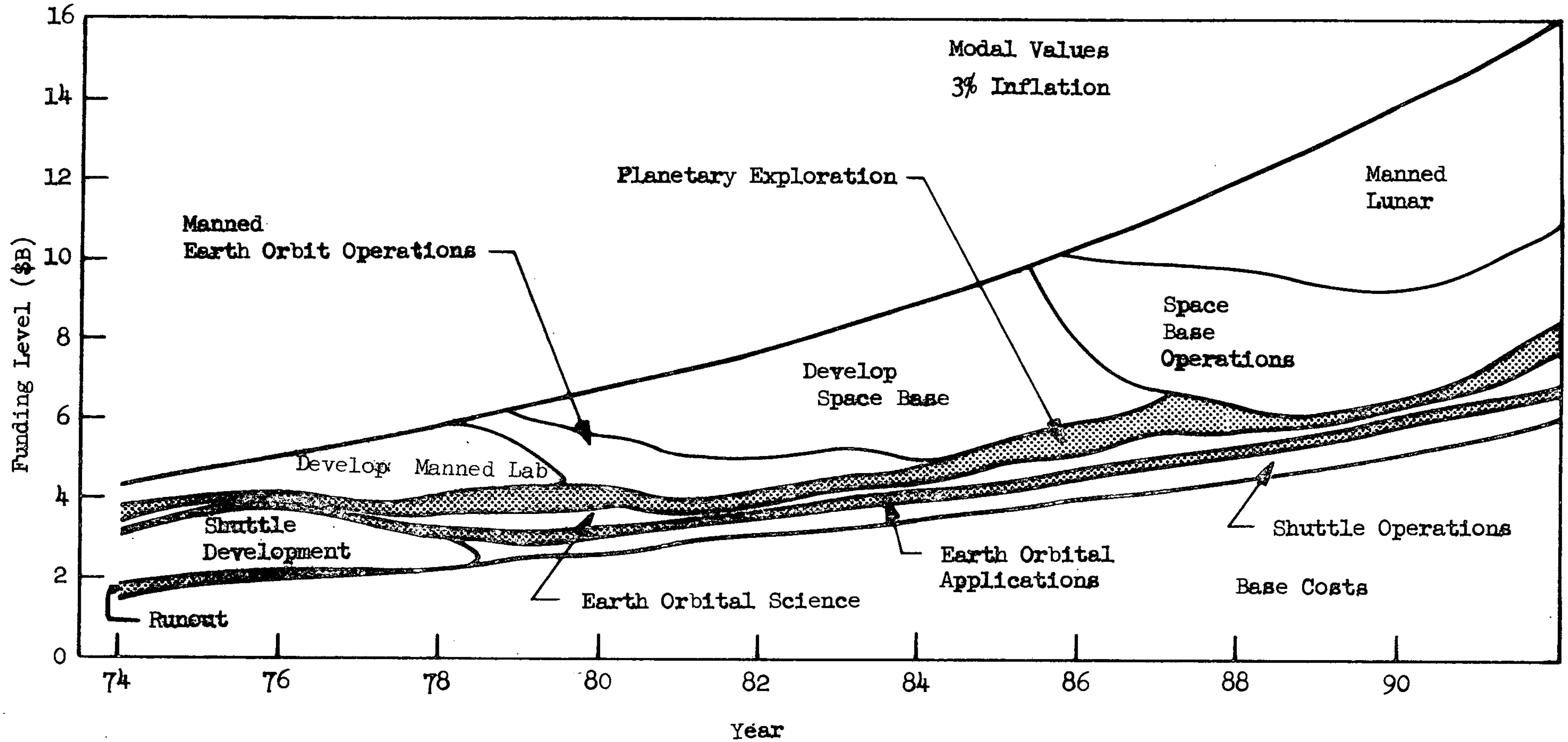

Fig. 4-1 Budget Allocation – Budget Level #1

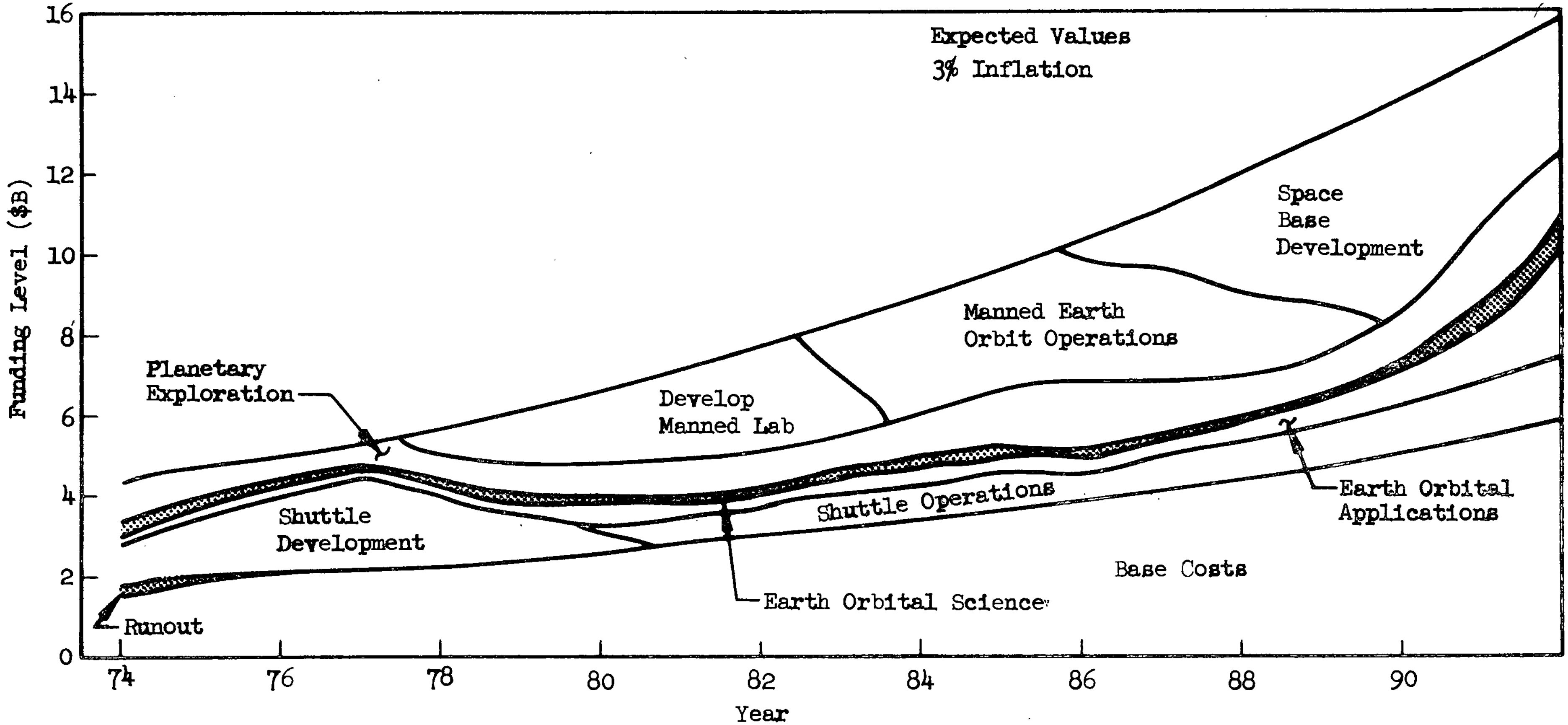

Fig. 4-2 Budget Allocation — Budget Level #1

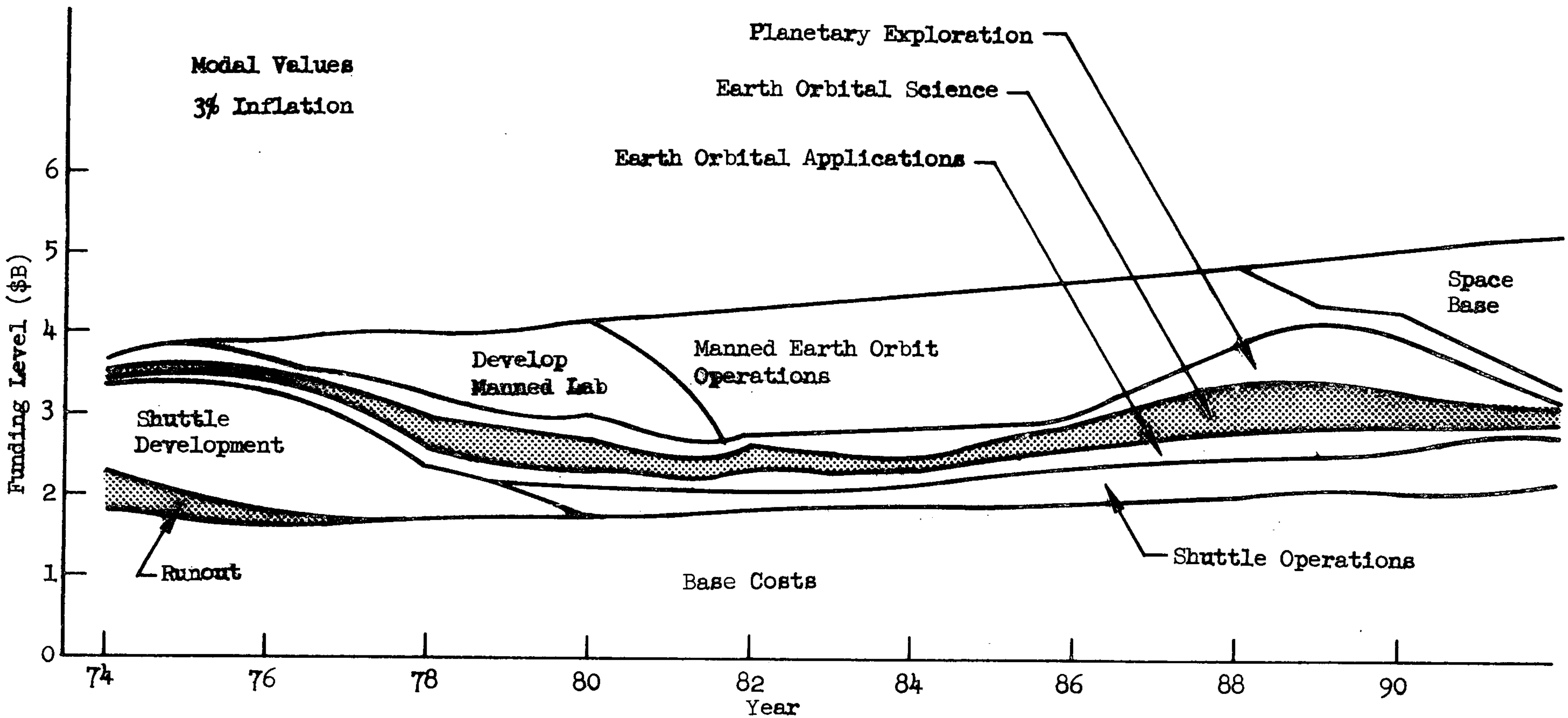

Fig. 4-3 Budget Allocation – Budget Level #2

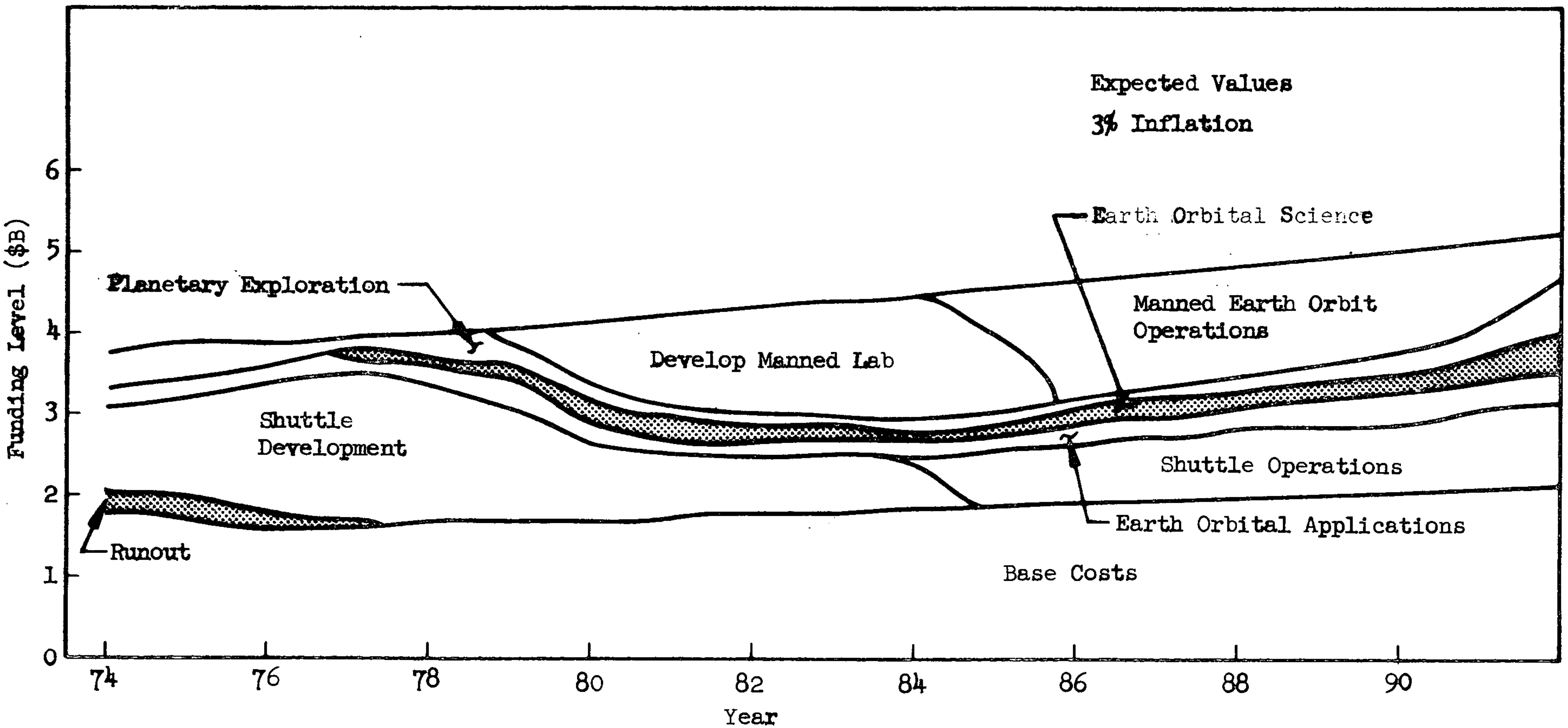

Fig. 4-4 Budget Allocation — Budget Level #2

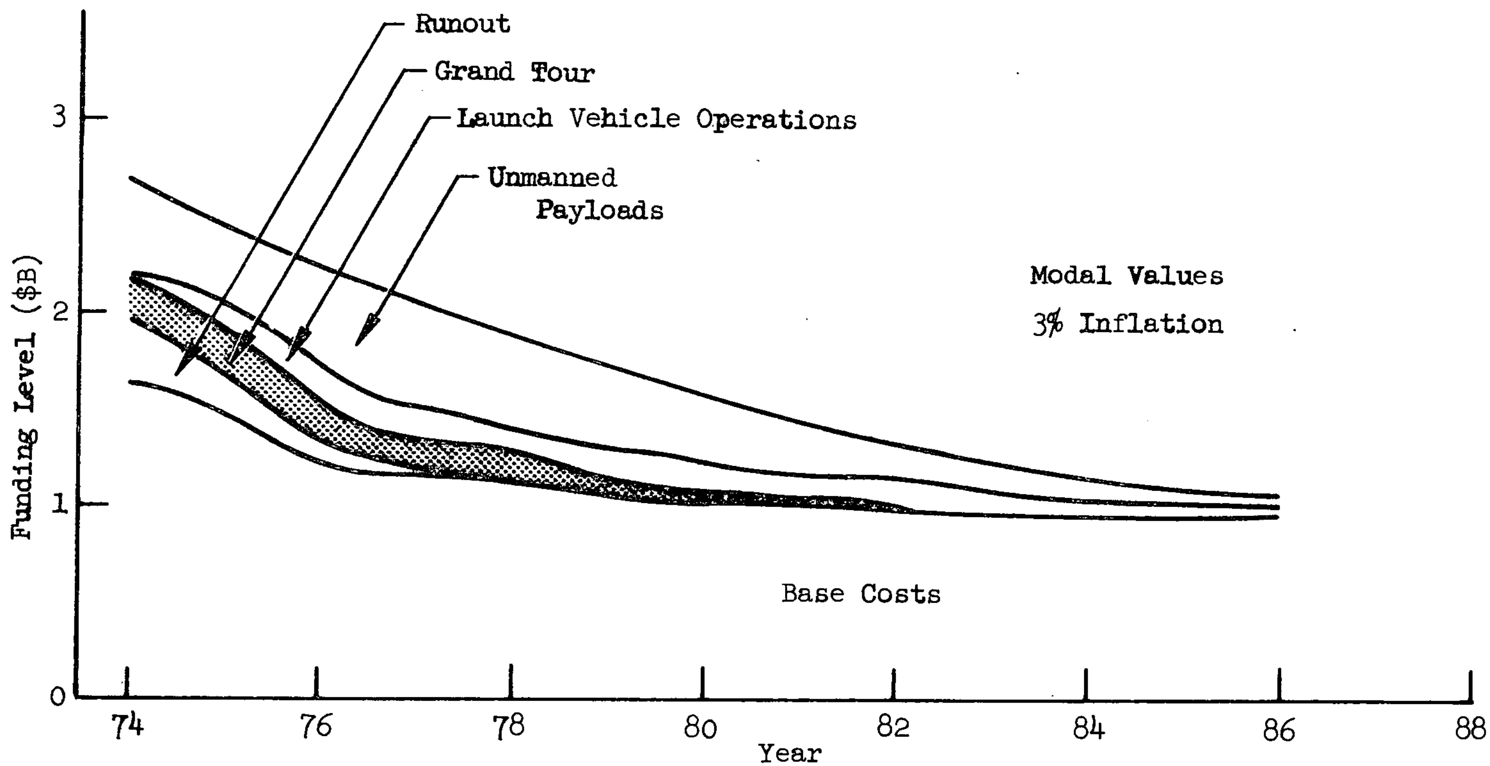

Fig. 4-5 Budget Allocation — Budget Level #3

a manned launch could occur earlier. The resulting program would not be as balanced as the one presented, however. Since expected costs are higher than modal costs for each program, some missions must be delayed if expected values are used and the same budget constraints are input. The impact of using expected values over modal values on the program composition and timing is apparent from a comparison of Figures 4-1 and 4-2 and Figures 4-3 and 4-4.

Although each profile was chosen for inclusion because it presented a balanced program and the reinitiation of manned space flight in the shortest reasonable time, each is not unique among programs with these attributes. Each total program does illustrate the number and type of missions which can be accomplished within the preset time period. Thus the general characteristics of a program which can be completed under the designated constraints is available for consideration. Further, while Figures 4-1 through 4-5 show major program categories, by using other output option selections fine grain detail can be output including every mission within a program and all the elements and their costs comprising each mission such as stages used, launch sites, payload, orbital characteristics, and other data appropriate to the level of interest of the analyst.

4.2 LAUNCH RATE SENSITIVITY

Within the given budget constraints, small changes can be made in the smoothing process so that slightly different launch schedules will be output. One such launch schedule for each level of appropriation is presented in Figures 4-6 through 4-8. The sensitivity of annual launch rate to the type of cost utilized, either modal or expected, is displayed. Since development programs must be stretched if the higher expected costs are used under a restrictive budget ceiling, the launch rate must remain low for a longer period of time until critical development programs are complete. Modal values result in higher launch rates

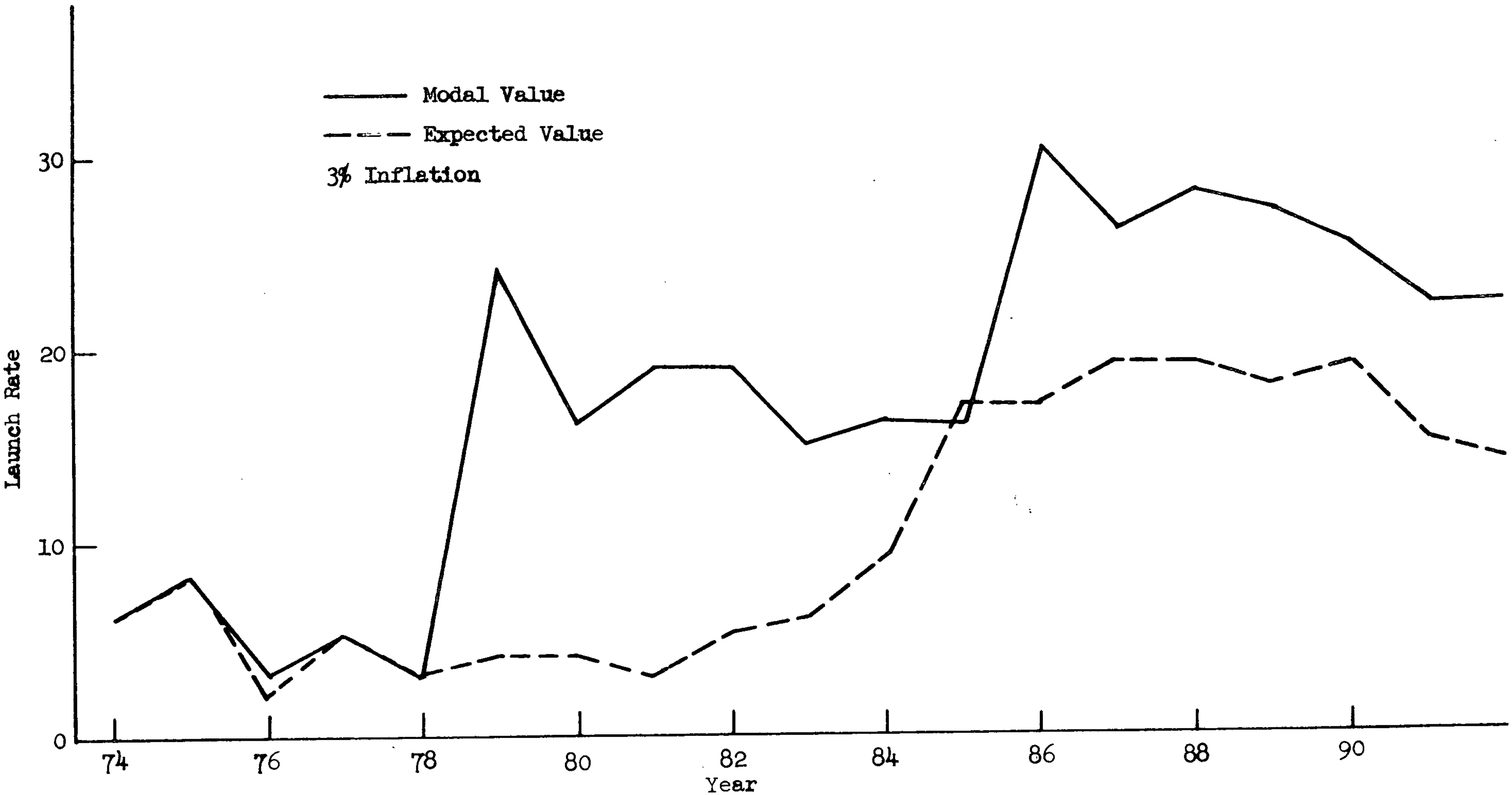

Fig. 4-6 Annual Launch Rate – Budget Level #1

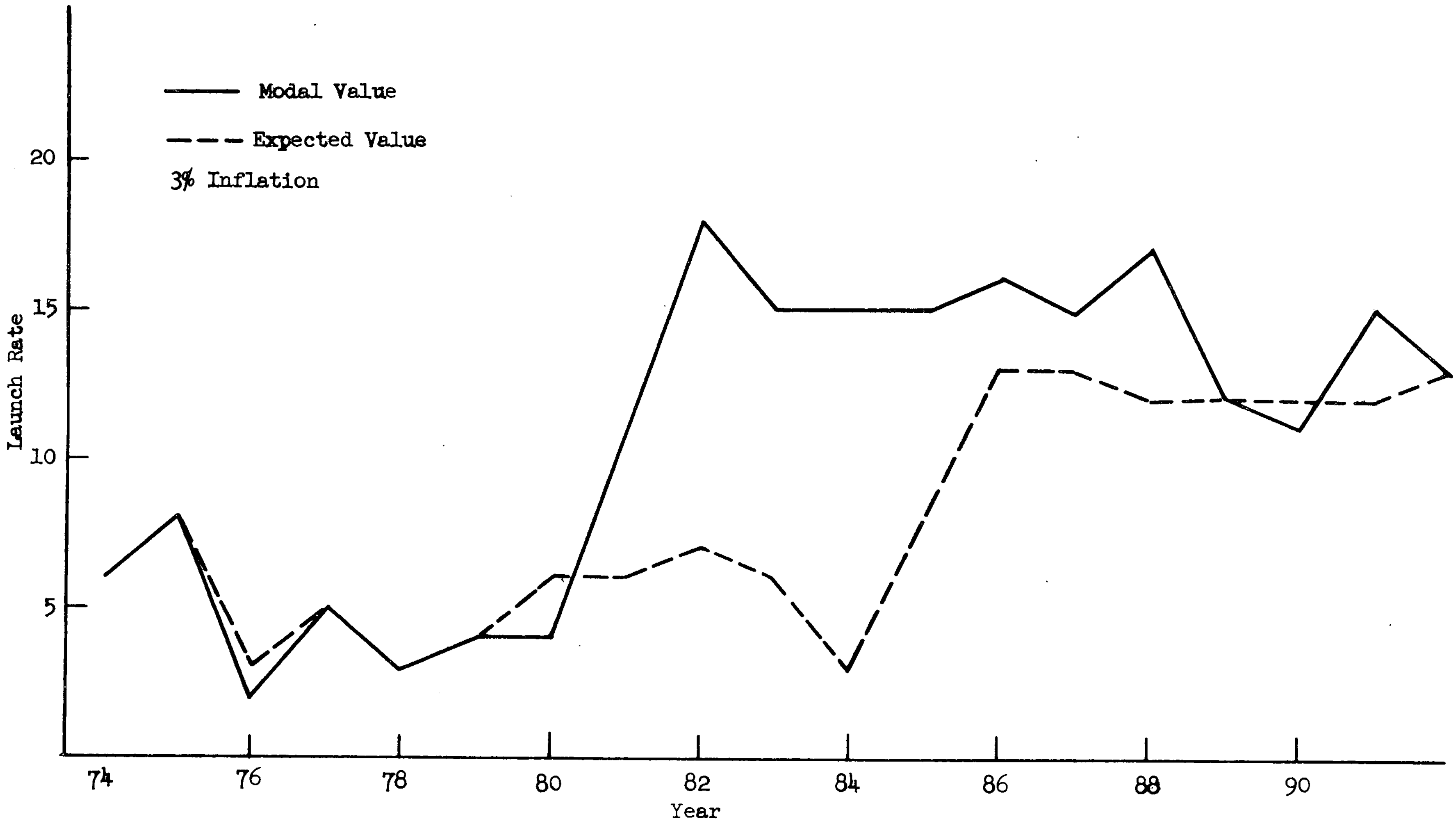

Fig. 4-7 Annual Launch Rate – Budget Level #2

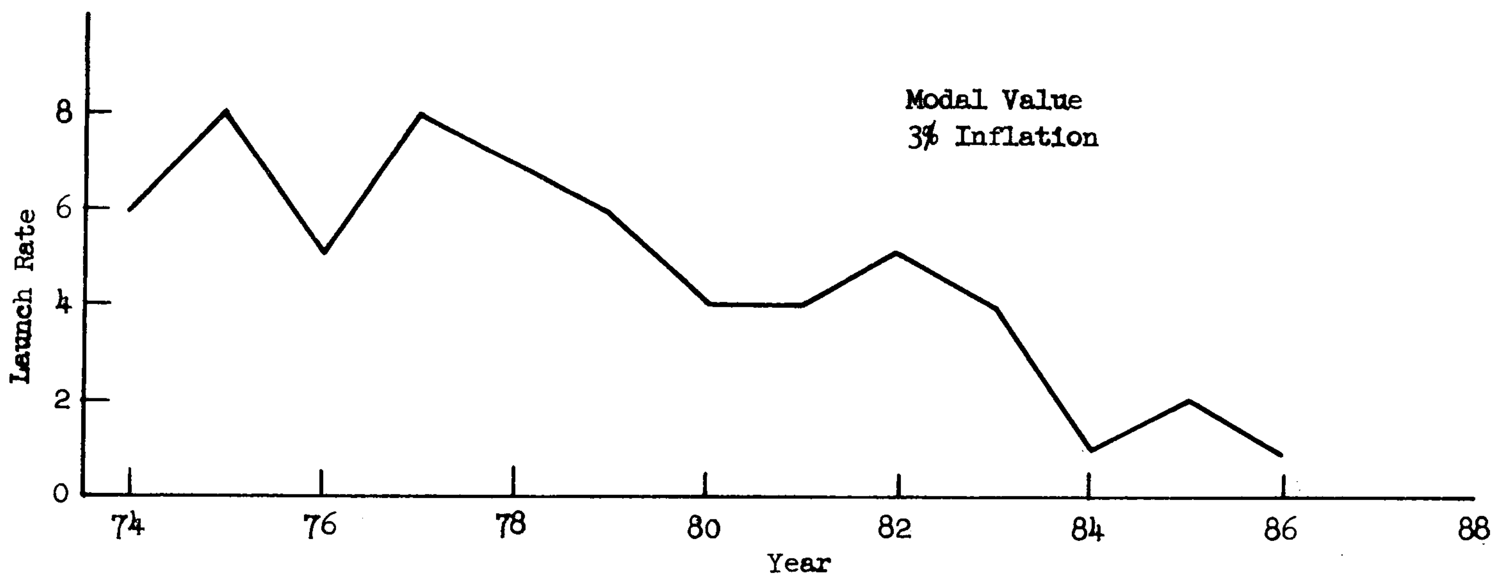

Fig. 4-8 Annual Launch Rate — Budget Level #3

5-6 years before these same increases can take place using expected values.

Figure 4-9 illustrates how the budget level affects the total number of launches over the 1973-1992 period. This relationship is not unique in the sense that some manned launches may be replaced by a larger number of unmanned missions. However, since each budget option was analyzed using the same set of missions as possible candidates and since smoothing was performed using the same guidelines for each budget option, the results have actually been normalized and only small perturbations in the results shown are possible.

4.3 TYPICAL PRESENTATIONS OF OUTPUT

The information presented in preceding sections is based on the assumption that the launch vehicle assigned to each mission in the program is optimal in the sense that the total mission program cost is minimized for this assignment and launch schedule. Thus, the optimal assignment features of the model ensures that the maximum space program is accomplished under each funding level.

Figure 4-10 indicates which launch vehicle is optimal for future manned missions as a function of traffic rate over a decade. The launch vehicle was selected from the list in Section 2.3 by the optimal assignment portion of the computer program. The results are thus quite dependent on the input cost data from Section 2.4. Using modal values, if there are less than 6 manned launches/year on the average, the 120" SRM + LS4B + CSM is the vehicle included in the least cost total program. It performs only the manned missions due to its high recurring cost. Unmanned missions are performed by existing vehicles. Similarly, if there are between 6 and 12 manned launches/year on the average then the 156" SRM + LS4B + S/C (reusable) is the optimal vehicle resulting in least cost for that program. It again performs only manned missions. If the average number of launches/year is over 12, then the modified

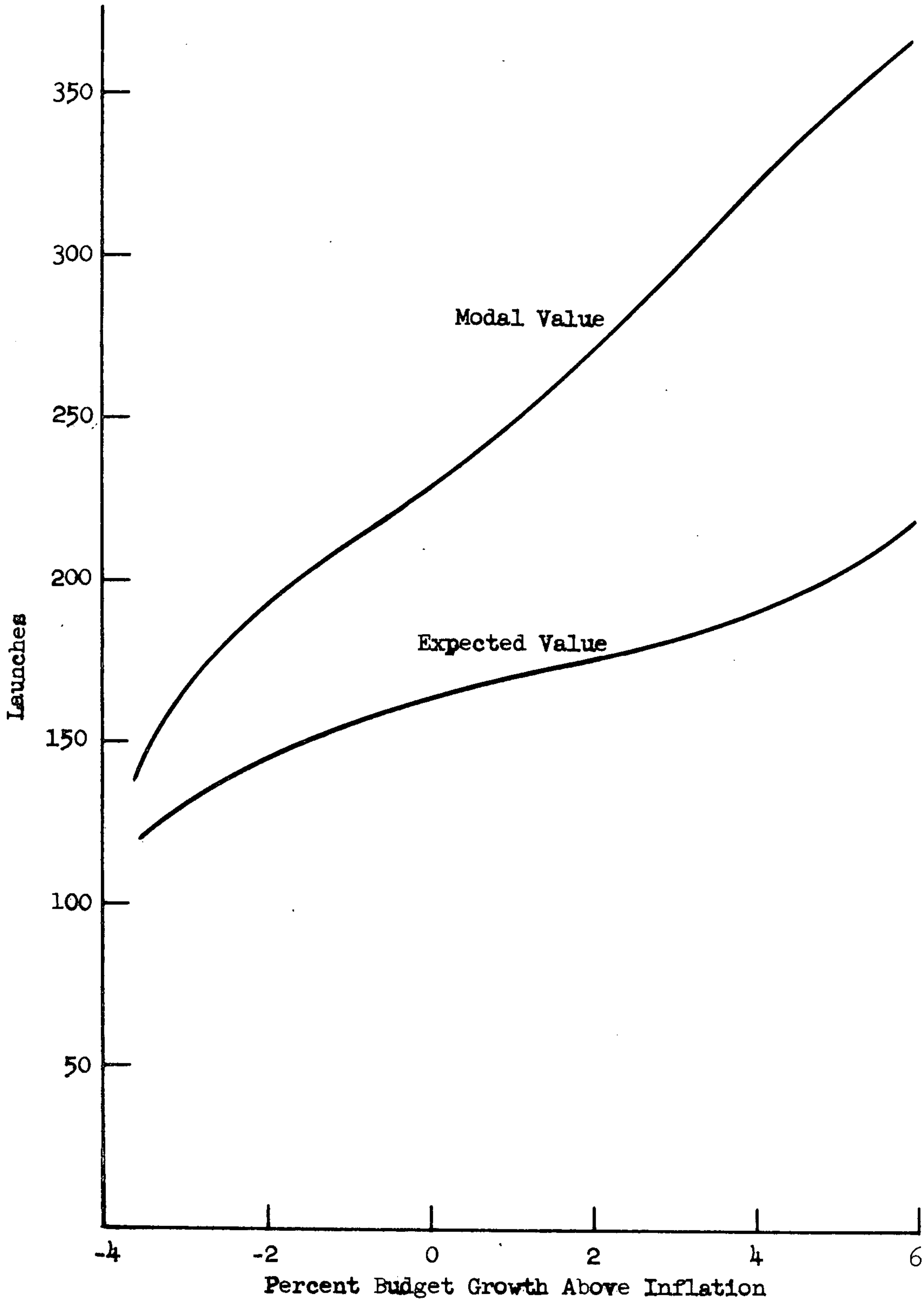

Fig. 4-9 Total Launches in 1973 – 1992 Period

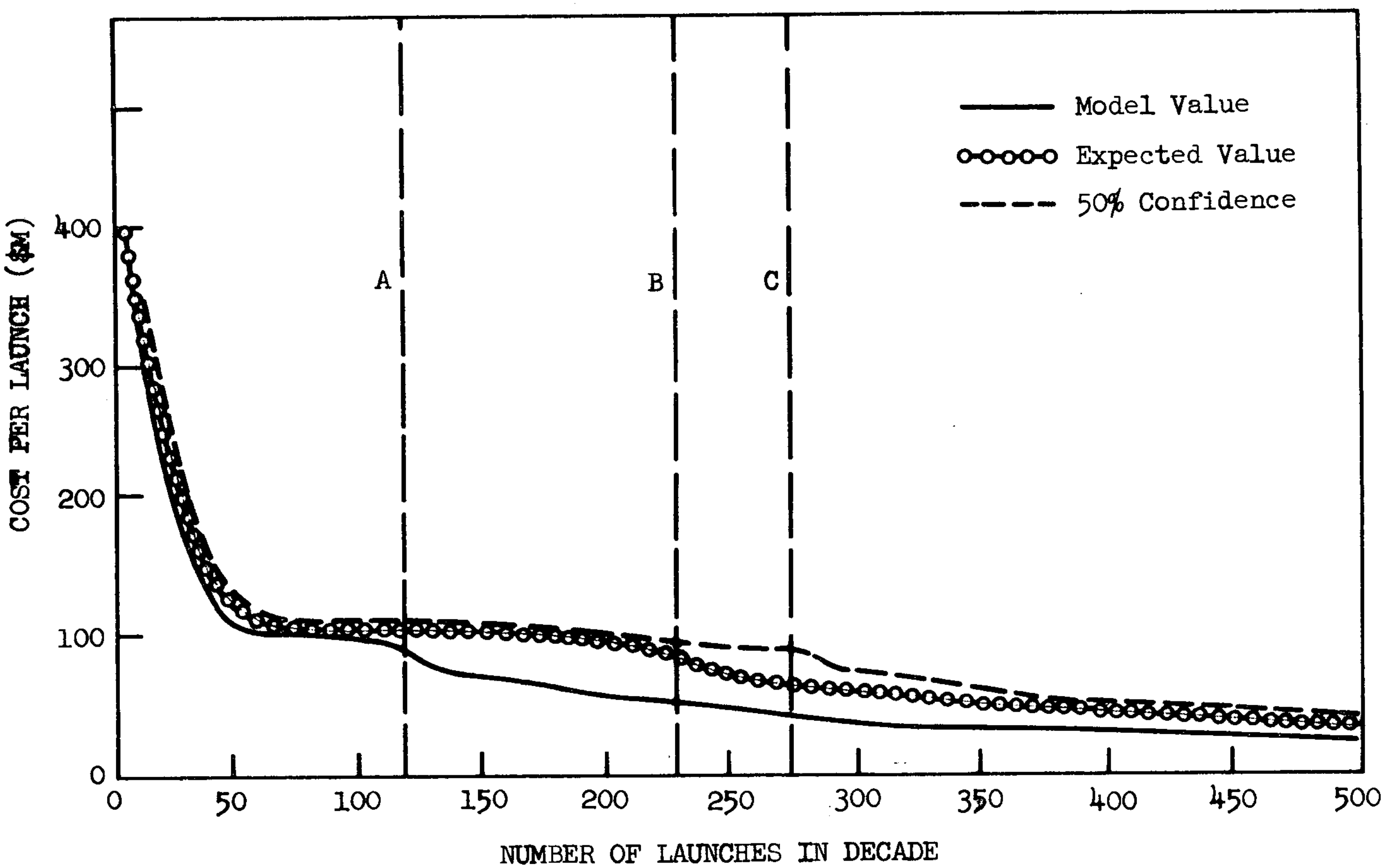

Fig. 4-10 Optimal Launch Vehicle Sensitivity

shuttle, described in Section 2.4, is selected as the optimal vehicle. In this case the modified shuttle performs all missions for which it is capable whether they are manned or not. The dotted line A designates the point where the expendable booster plus reusable spacecraft ceases to be the optimal launch vehicle using modal values. The region to the right of line A is based on the modified shuttle as optimal vehicle. Line B provides the same boundary as Line A but for expected costs. Line C is this same boundary based on a 50% upper cost bound. Thus, to the left of line A the analyst is 50% confident that an expendable booster plus reusable spacecraft is the optimal launch vehicle. To the right of line C (up to 1000 launches), the analyst is 50% confident that a modified shuttle is the optimal launch vehicle. Between lines A and C, the optimal vehicle is chosen based on other considerations than cost per launch, such as budget constraints and importance of restarting manned space flight in the near future. The analyst is 50% confident that the cost per launch will lie between the lower and upper curves in any launch rate region. For this analysis the cost per launch was determined by taking the total cost, including development, total refurbishment, total sustaining, investment and inventory costs based on a 45 day initial turn-around-time, and dividing it by the total number of launches over the decade beginning in 1979. Because all partially reusable and fully reusable vehicles were assumed to have the same performance characteristics, variable turn-around-time as a function of alternate reusable vehicles did not enter this present analysis. This and the effects of other potential variations between alternate reusable concepts would be desirable to include in subsequent analyses to evaluate their sensitivities.

Another form for presenting output from this model is indicated on Figure 4-11. A series of runs, such as those described in section 4.1 were made for various budget growth levels. The percent increase above inflation began in fiscal year 1975.

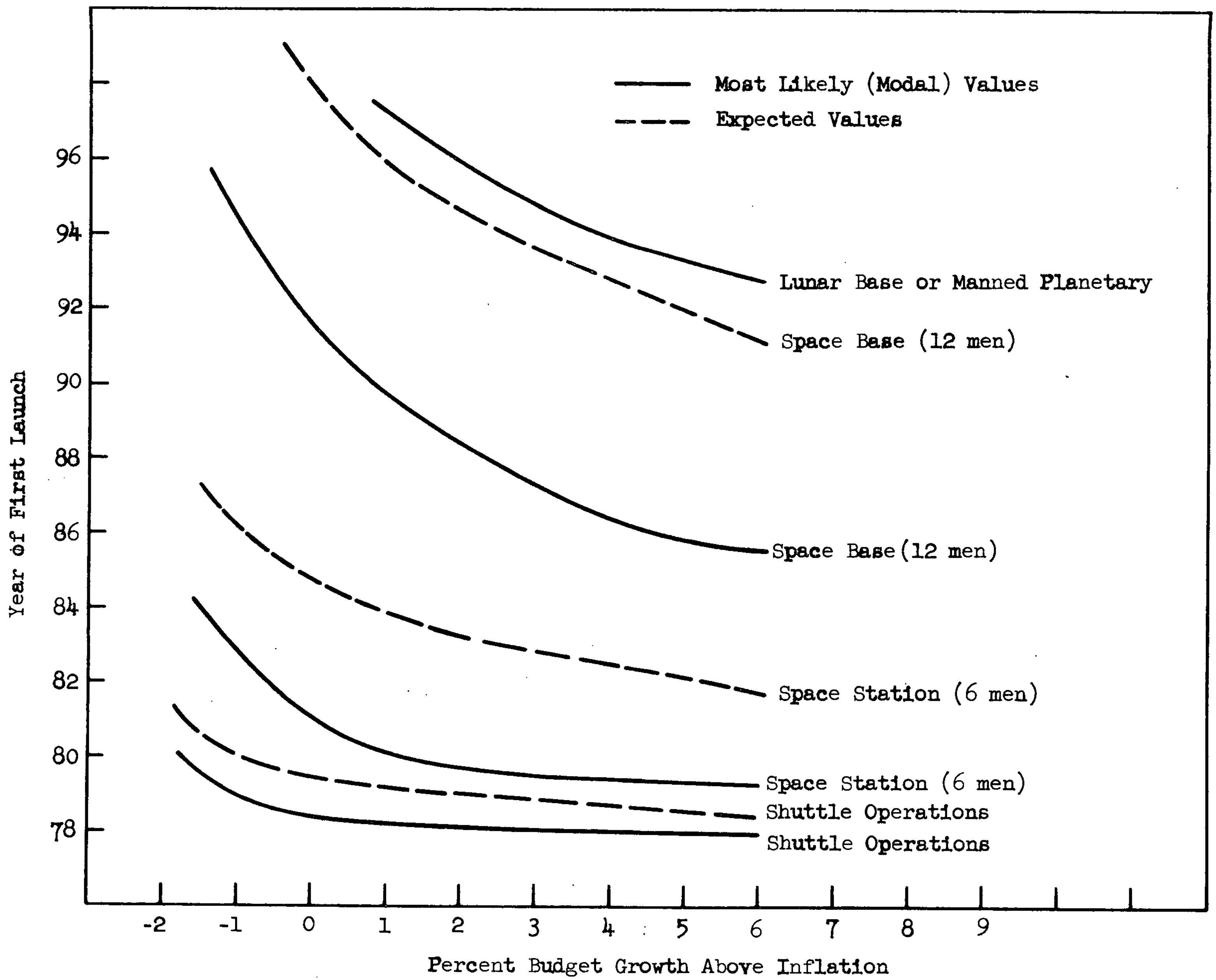

Fig. 4-11 Sensitivity of Program Content to Budget Level

The funding levels for fiscal years 1973 and 1974 were based on historical trends established in section 2.1. Each curve in Figure 4-11 is part of a balanced program with the reinitiation of manned space flight in the shortest reasonable time. Unmanned programs are maintained at a viable, although not ambitious level. Each curve includes the program preceding it. Thus the Space Base with 12 men may be launched in 1986 if the budget allocation grows at a $4\frac{1}{2}\%$ level (above inflation). In this same program, a 6-man space station is launched in 1979 and shuttle operations begin in 1978. The sensitivity of initial launch date to use of expected values rather than modal values is indicated by the displacement of dotted curves from the solid curves. As the budget allocation is gradually reduced (in "real" dollars) the initial launch dates of these programs increase until they no longer may be considered viable alternatives in a future mission plan.

It is apparent from these selected presentations of output that risk assessment in the development and operation of advanced technology systems has significant impact on the identification of optimal candidates for launch vehicles and viable programs for a mission plan. This resource allocation model, which utilizes an historical data base to quantify the varying degrees of risk in costs and other entering parameters, therefore, provides realistic results and in a form readily used by the advanced planner and decision maker.

Section 5

NEW PROGRAM DIRECTION DECISION METHODOLOGY

The significant investment in the national space program over the past decade and extending into the next decade provides both the technology and operational plant that can potentially solve important national problems. Utilization of this space investment can be applied in two areas: (1) more effective and efficient solutions of existing problems (e.g., worldwide telecommunications, navigation, weather and other earth surface surveillance requirements, more precise determination of geophysical and other scientific data for the solar planetary system including the earth, and others), and (2) the utilization of space for new national requirements. This second category is of particular interest if resulting applications can improve national productivity by developing a space application which satisfies a growth commodity or service. The growth area can be one which reflects existing public demand or develops into the growth region by synergistic effects.

This section develops basic decision criteria and related methodology for identifying significant new space program directions - i.e., space utilizations in both categories (1) and (2) above but emphasizing those in the latter category. Also production runs are described in which generic examples of growth commodities and services requiring space utilization are superimposed on presently planned national space mission models.

5.1 PROBLEM DISCUSSION

In prior tasks under this contract analysis of data from large scale production runs using the optimal resource allocation model for the national space program showed that significant cost savings are possible using fully reusable space transportation vehicles, but payoff crossover compared to expendable systems occurs in the higher launch rate region. The effort in this task therefore is to develop basic decision criteria and related analytics which can be used to identify potential new directions for the use of space resulting in increased traffic demand and therefore reduced space utilization costs for all users.

Data that is available for new program direction analysis is primarily of a predictive nature. Decision criteria have therefore been kept simple and compatible with these data sources. Also only criteria which are quantifiable have been included.

The methodology utilized as a primary approach provides for decision on a break-even, cost vs. profit basis. The use of quantifiable criteria and the related selection methodology provides a realistic, but somewhat conservative decision basis for evaluating candidate growth commodities in space applications. Certain other criteria, presently of a more subjective nature, also contribute to the payoff of providing services and commodities through the use of advanced space concepts. These include earth environment control, the benefits to earth oriented problems by use of advanced technology developed in advanced space efforts, and others. Certain of these elements are rapidly being quantified; for example, a tax or cost penalty added to earth produced commodities or services when their production degrades the earth environment. Thus this element can be entered in unit cost and included in cost comparisons between earth and space approaches. Refinements to the decision criteria and related methodology which reflect many of these presently subjective elements can be added to refine the present decision analytics and better define break-even contours of cost and benefits.

5.2 GROWTH COMMODITY OR SERVICE

An assumption provided by the work statement for this phase of effort is that space utilization will grow in a manner typical of a growth commodity. The rationale which supports this assumption has been indicated at the start of this section. As a basis for developing criteria which can aid in the identification of growth commodities for future space applications, either on an individual or synergistic basis, growth commodities are briefly discussed in the following paragraphs.

Historically, growth commodities (industrials, services, etc.) have shown common characteristics (Ref. 3). The most significant are:

- An up-turn time
- Exponential slope (greater than GNP slope)
- Variations in slope during rise (greater slope, higher growth; lower slope, less growth)
- Sustained duration of growth before turn-over. Normally for a mature industry, this will be a slope approximately parallel to GNP
- Magnitude attained before turn-over. This will vary for different commodities and depends on the percentage the commodity represents of the total GNP
- Commodity growth slope starting magnitude (initial amplitude)

The preceding growth commodity characteristics are shown on Fig. 5-1. On the figure the ordinate can be variously dimensioned (i.e., dollars, launches, lbs, etc.) while still retaining characteristic growth commodity identifying features. A significant innovation, invention, or technological breakthrough when coupled with public demand is normally the cause of the emergence (up-turn) of a growth commodity. Public demand is generally based on the new availability of a significant new service, a marked reduction in commodity cost

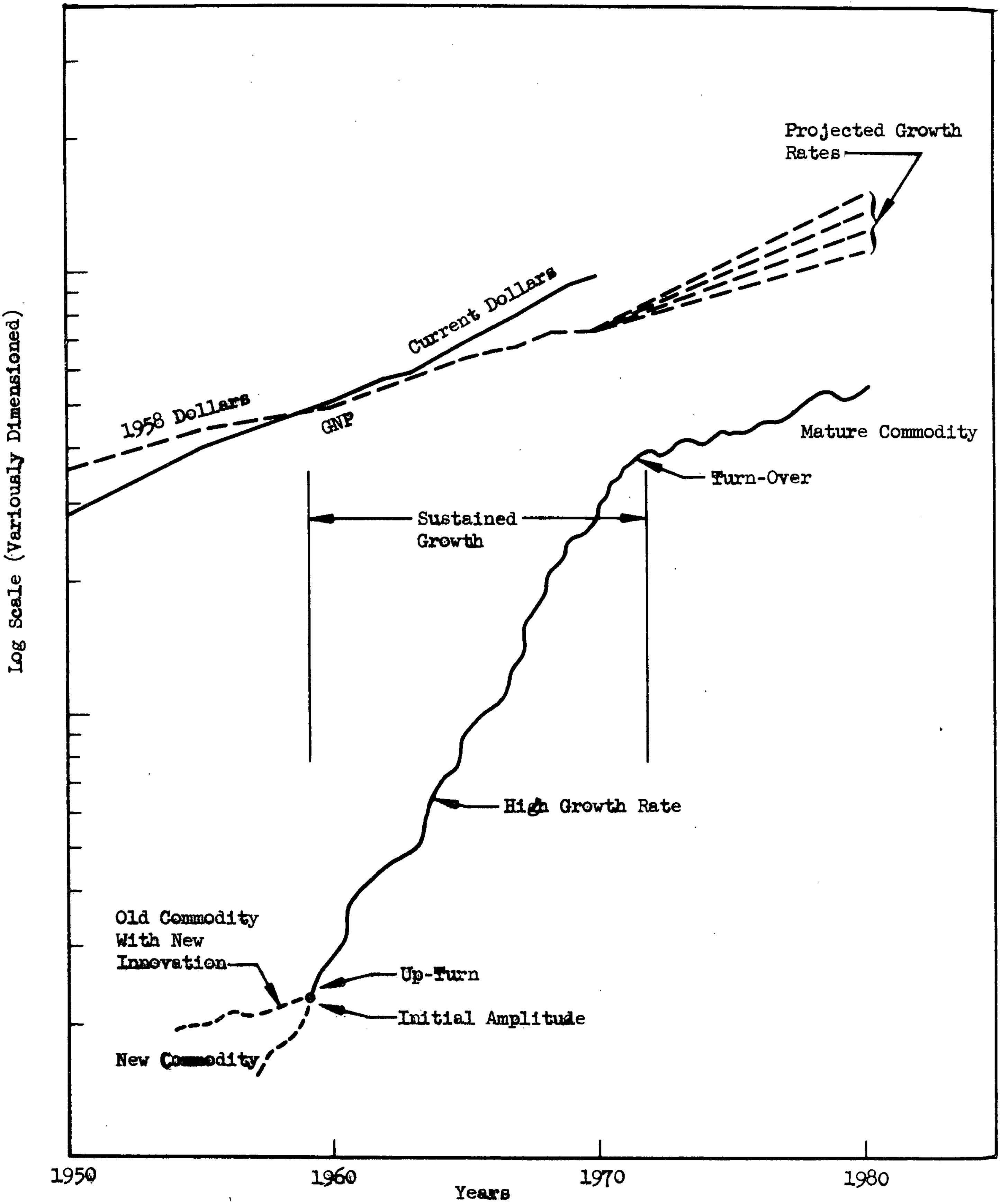

Fig. 5-1 Characteristics of Growth Commodity or Industry

or increase in quality, or in some cases by an external driving force, e.g., national defense or the preservation of a livable environment. When the internal innovative thrust of the commodity is lost or demand is satisfied, the growth commodity decreases slope to that approximating GNP or declines further.

5.3 CRITERIA

Characteristics of a growth commodity and other related factors which are important in the development of an analytic approach for identifying growth commodities and their potential application to future space utilization are discussed in paragraphs which follow.

Gross National Product (GNP) - This parameter is statistically tracked and predicted by government agencies (Refs. 4,5) and is widely used for various economic analyses. It is the value of total U. S. production of goods and services. Normally it is expressed on two bases: in current year dollars, and in real or actual dollars adjusted to some preceding year as a base to account for the change (increase) in prices during the period since the base year. Fig. 5-2 shows a plot of GNP both in current year and 1958 dollars as well as projected real (deflated) parametric growth rates.

Expressed in current dollars GNP includes two basic components: the actual worth of the goods and services, and the inflating effect of price increases. To use GNP on a projected basis both components must be predicted. Historically there has been more success in projecting the actual value component of GNP. The evaluation approach discussed in this section is primarily interested in comparing projected, real values of commodities with the GNP. Therefore the constant dollar GNP is used as a criterion. To provide for prediction variations, GNP growth rates are also entered parametrically.

Up-Turn - This is the point in time at which a growth commodity

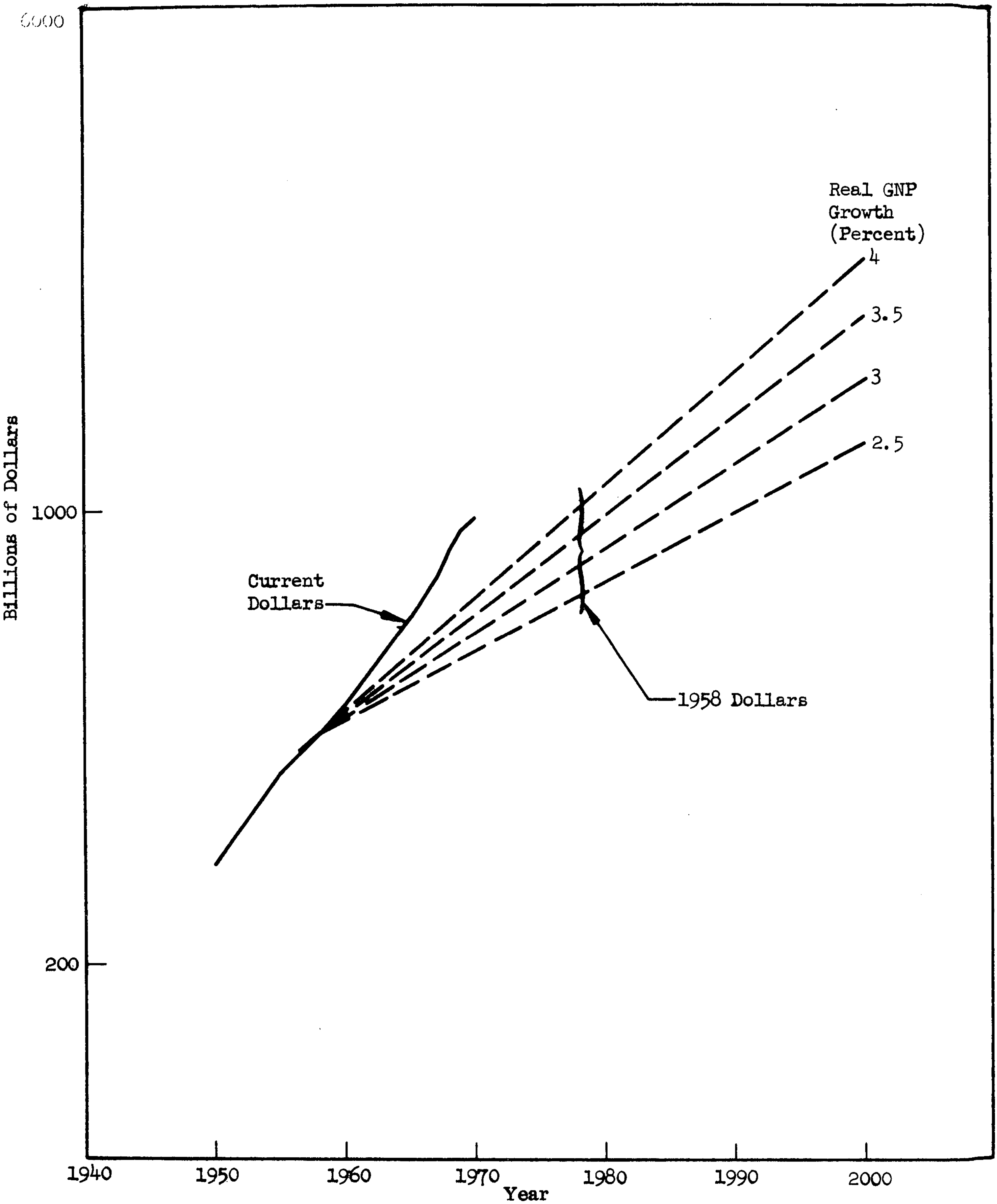

Fig. 5-2 U.S. Gross National Product vs Year

exhibits rapid increase in slope. It normally follows an innovative breakthrough. An up-turn can be predicted by technology analysis to establish time feasibility and economic analysis to determine demand and cost viability. Generally the economics can be less exactly predicted than the technology. In a following illustrative example (section 5.5), up-turn will be taken as an expected availability date of the reusable space shuttle - 1980.

Initial Amplitude - This is the value of demand (after experimental testing) at which the commodity starts up the growth slope. It occurs at the "time-on-line" for a start-up industry. It will vary with commodity and can be variously dimensioned for analysis, e.g., number of units which represents the consumption of the commodity, or it can be reduced to the dollar value of the commodity.

Growth Rate - The slope at which the demand rises can be predicted by analysis or can be treated parametrically. In the methodology developed in this study, it will be handled parametrically.

Turn-Over - The time at which commodity demand stops growing at its elevated slope and parallels the GNP slope or turns lower is again a parameter that can be predicted by combined technological and economic analysis. If cost alone is the payoff decision variable (no external forces acting), turn-over should occur above the break-even threshold so that return from commodity sales will exceed costs expended.

Break-Even Threshold - This is the level of delivered commodity that must be reached for the commodity exploited to break-even. If, as discussed above, the decision is based on cost payoff alone, this threshold is determined at the point when the cumulative investment and operations cost curve intersect the income return curve from the delivered commodity. At this point the new undertaking becomes profitable. In many cases, factors other than cost enter. In these cases, the decision threshold reflects the inclusion of these factors, e.g., national defense, environmental gain, societal advancement, etc.

5.4 ANALYTIC APPROACH

In developing criteria and an evaluation approach for identifying growth commodities that can have application to future space utilization, two analytic expressions are of interest. One of the more important aspects is the rapid assessment of rate of growth. This characteristic is illustrated by the doubling interval

$$C = A\,2^{\frac{Y_t - Y_{ut}}{n}} \Bigg|_{n = 2,3,6,10\ldots} \qquad (5.1)$$

Where A = initial number (magnitude) of units required

Y_{ut} = year of up-turn

Y_t = a future year

n = number of years required for doubling

C = number of units required in year Y_t

An example of this is shown on Fig. 5-3, where A = 3, Y_{ut} = 1970, and doubling is on a 6-year cycle (i.e., when Y_t = 1976, 1982, etc.). This shows that 6-year doubling represents significant growth when compared to GNP (see Fig. 5-2). On Fig. 5-3 growth slopes are indicated for 2, 3, 6 and 10-year doubling.

As a real-world example, Fig. 5-3 also shows the total energy consumption in the United States. This curve was derived from statistical data developed by an international organization (Ref. 6) for the period 1951 through 1965. In developing this curve from the raw tabular data, various factors were considered. These included the varying energy content of basic energy fuels, appropriate conversion efficiencies, all significant types of energy consumed, and others. From this curve

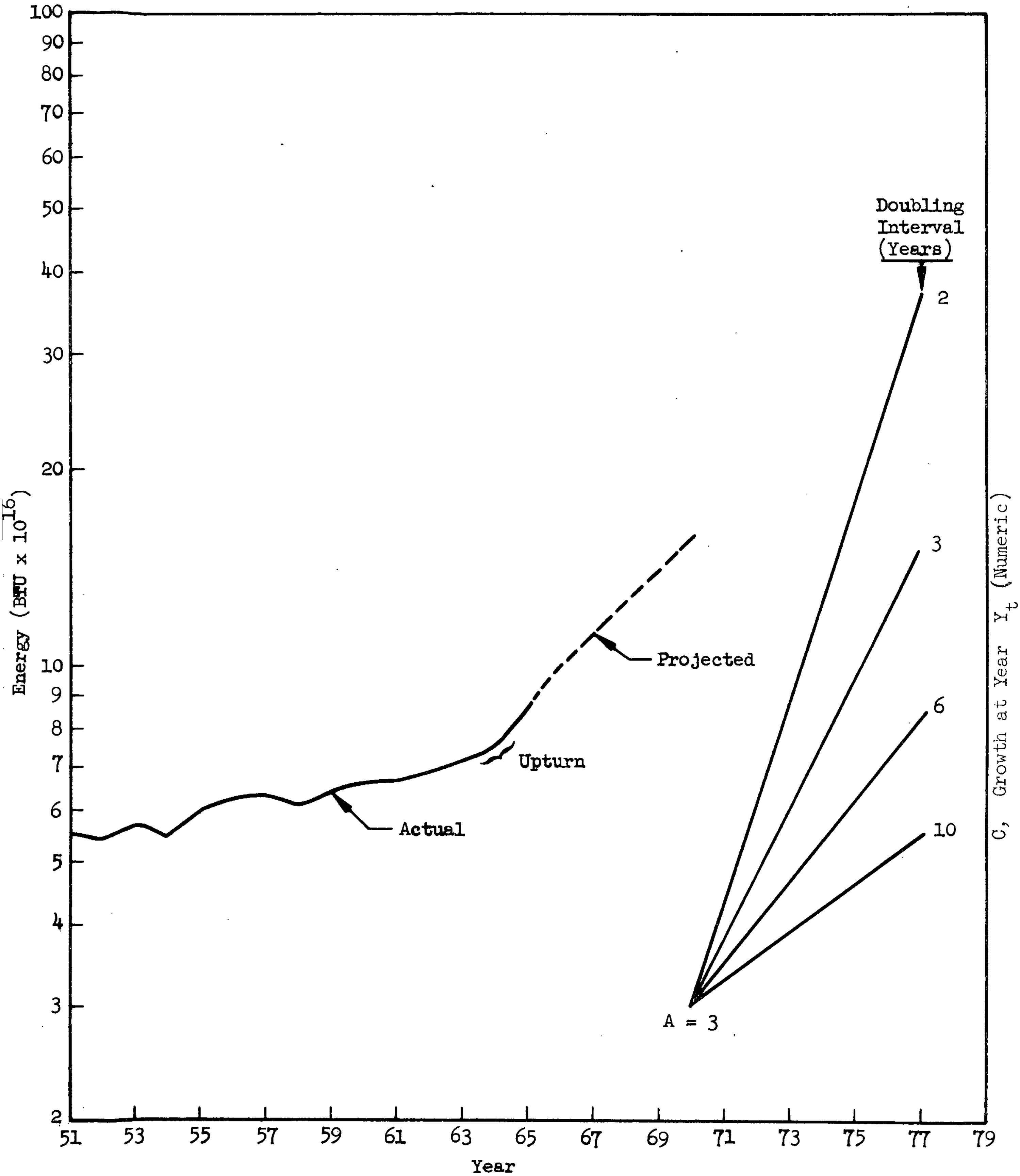

Fig. 5-3 U.S. Energy Consumption and Doubling Growth Intervals

it may be noted that during the period 1951-1963 the energy consumption had an approximate growth of 4.5%. However at about 1963-1964 an upturn took place and consumption rate increased significantly. Based on extrapolation of this data energy consumption apparently now has a growth rate in the range 6-8%. Compared to the average growth rate of the real GNP of about 3.6%, energy is a good example of a growth commodity.

An equivalent expression to (5.1) is

$$C = A\ (1 + \gamma)^N \qquad (5.2)$$

where γ = rate of growth

N = number of years after initial up-turn

C and A remain the same as in (5.1)

This expression is more advantageous analytically than (5.1) in that growth rates can be directly compared numerically to GNP slope, values are tabulated in normally available tables, and it includes the significant factors for decisions on growth commodity applications.

Steps used in applying (5.2) and the existing optimal space program resource allocation model to evaluate a selected growth commodity for viability as a future space application are briefly summarized below.

1. For selected growth commodities determine the year of up-turn (Y_{ut}), rate of growth (γ), and initial amplitude (A) (can be in dollars of worth, units appropriate to the commodity, or simply in launch loads). Values for these elements can be determined by an analysis of demand or expressed parametrically around an estimated value.

2. Exercise the space optimal resource allocation model using the added traffic load in 1. above. Include this new traffic in the total mission model to provide optimal utilization of contemp-

orary space program hardware and services. Derive investment and operating costs for the selected commodity(ies) as components of the total optimal space program. If 1. is done parametrically, derive best values for γ, A, and Y_{ut} for the optimal space program.

3. Using values defined for Y_{ut}, A, and γ, and the investment and operating costs for that commodity, solve (5.2) to get N, the number of years the demand has to continue to return the investment. If A, γ, and Y_{ut} have been handled parametrically, values for N will be break-even contours rather than point values.

4. Perform iterations using the model varying parameters (over which control can be exercised) to optimize return on investment plus operating cost for that commodity.

Fig. 5-4 and the previous Fig. 5-1 provide data which illustrate this procedure as it applies to a typical growth commodity. For simplicity in presentation, single values are used for parameters which would normally be treated parametrically - time of up-turn, initial amplitude, growth rate, time of turnover, projected actual GNP growth rates.

The approach shown in Fig. 5-4 can be applied to make decisions as to the viability of a new concept or a mix of new concepts superimposed on existing national space mission models - funded and/or planned. In performing a typical evaluation the following elements are computed as they apply to a growth commodity or mix of commodities with potential as new space applications:

- Commodity development cost and time-on-line
- Annual mass requiring transportation to (and from) space orbit and number of corresponding space transportation system (STS) loads (dependent on altitude and inclination).
- The wholesale value of an STS load of that commodity.

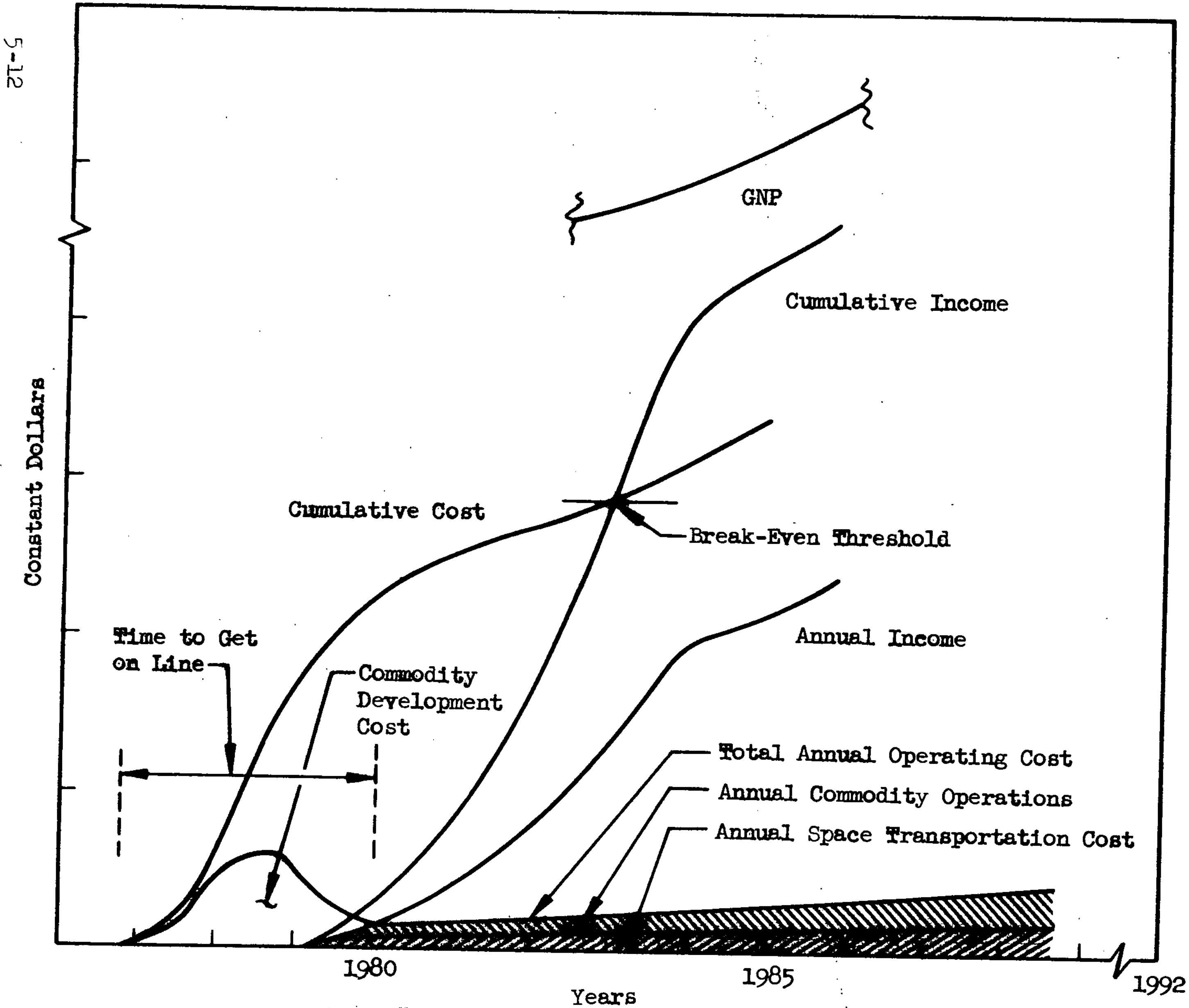

Fig. 5-4 New Space Concept Economics

- Annual pro-rated share of the STS costs for that commodity

From these data and the characteristics of the growth commodity (section 5.2) the remaining parameters on Figure 5-4 and the viability of the new space concept can be determined.

Section 5.5 provides illustrative examples of computer model runs which determine STS costs applicable to new space applications.

5.5 EXAMPLE APPLICATION

An illustrative example of the preceding methodology is presented in this sub-section. The anticipated profit or quantifiable benefit (Section 5.1) from any potential growth program is quite dependent on the transportation costs necessary to implement and operate the new program. Evaluation of the potential use of space for any growth program therefore requires an estimate of these related transportation costs. For this purpose three growth programs, each with a different exponential growth rate were superimposed on the two NASA mission profiles corresponding to Budget Levels #1 and #2. The smoothed programs associated with these levels are discussed in section 4.1. The launch rate required by the growth program is determined by equation 5.2 repeated here for convenience.

$$C = A\,(1 + \gamma)^N \qquad (5.2)$$

where Y_{ut} = 1980 = year of initial upturn

C = Number of launch loads required in year N after initial upturn

A = initial launch rate in year Y_{ut} = 3 launches per year

and γ = rate of growth

= 0.414 for example 1

= 0.26 for example 2

= 0.125 for example 3

The launch schedules for these three growth rates are shown in Figure 5-5. Production runs of the space optimal resource allocation model were made using these three launch rates superimposed on the two budget levels of interest to determine launch vehicle transportation costs. For each run an optimal launch vehicle mix (including both expendables and reusables) was selected based on the input payload and velocity requirements. Three sets of velocity requirements were input for each growth rate: (1) all payloads delivered to near-earth orbit (2) all payloads delivered to synchronous equatorial orbit and (3) one-half the payloads delivered to low-earth orbit and the other half to synchronous orbit.

Results from the production runs show that a modified shuttle or shuttle and appropriate upper stage combination was the most economical mode of transportation for the growth program given that the smoothed NASA program was underway. The costs included in this analysis are described below.

<u>Recurring Cost:</u> Recurring costs for the shuttle and expendable upper stages are presented in section 2.3. A 90% learning rate was applied to these first unit costs. The same learning was applied to refurbishment costs, in that these costs will also decrease as experience is gained in the recycle procedures required and as new techniques become available for use.

<u>Investment Cost:</u> Additional vehicles are required besides those necessary for the NASA smoothed program. A 13-year lifetime was assumed with a turn-around-time from recovery to relaunch of 45 days initially. This turn-around-time was decreased by a learning factor so that a one-week turn-around was available by 1992. The total expected investment cost, taking reliability into consideration, was amortized equally over the launch period for each case. Five vehicles were required for the growth rate 1 program, three for the

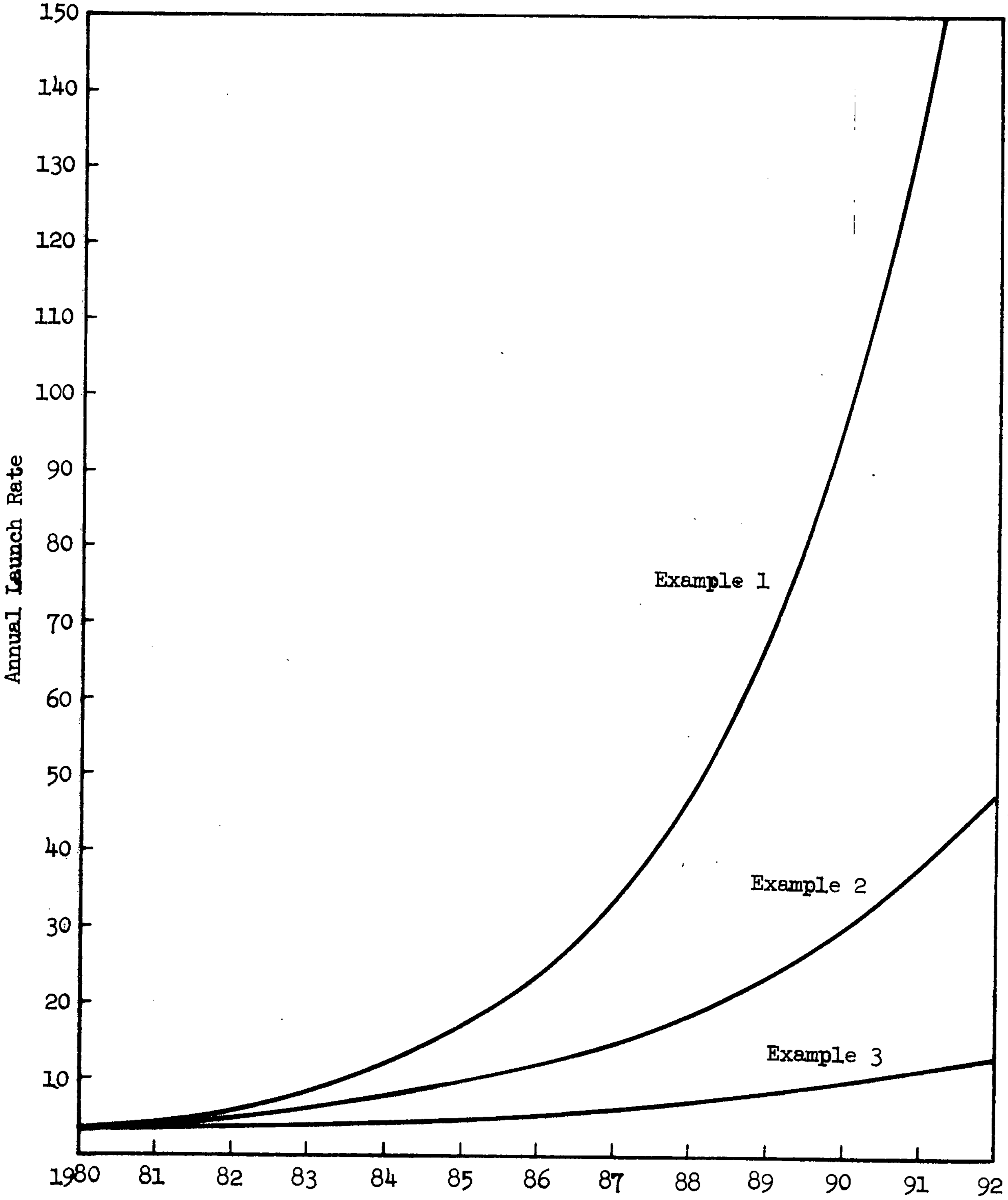

Fig. 5-5 Growth Program Launch Schedules

growth rate 2 program and two for the growth rate 3 program. (Each case included one vehicle for back-up).

Development Cost: The development of the shuttle is assumed to be complete by 1980 and all expendable upper stages considered are assumed to be available at this same date. Therefore these development costs are not included in this analysis. However, the development costs associated with new launch pads and new refurbishment facilities to handle the increased traffic rate was estimated and prorated equally over the launch period 1980-1992.

Sustaining Cost: The sustaining costs presented in section 2.3 were allocated between the NASA budget and the growth program under consideration according to use. In addition, increased sustaining costs due to an increase in refurbishment, launch facility and program management personnel was included.

The above costs were considered by the resource allocation program for the two budget funding levels discussed in section 4, the three growth rates and the three mixes of characteristic velocities presented above.

Total costs attributable to each growth program were output for each year of interest. These annual expenditures fluctuated somewhat due to changing launch rates in the NASA program; however, annual costs for each growth program were lower using the more ambitious budget level #1 than those for budget level #2. The annual costs increased in time as the launch rate increased due to exponential growth; but in this same time period NASA launch rates were increasing and learning effects were significant, so the net increase in cost was at a lower exponential rate, thus providing a cost benefit to the growth commodity.

The results were averaged to show trends. Since the conclusions based on budget level #2 were similar to those for budget level #1, Figures 5-6 and 5-7 are based only on budget level #2. Figure 5-6 shows the averaged annual expenditure above the given NASA funding level for the three characteristic velocity requirements as a function of exponential growth rate.

The launch rate for each growth program was also averaged so this number could be divided into the corresponding average annual expenditure to produce an average cost per launch for each case. The payload in pounds for each launch to a specified characteristic velocity is also known. Thus the average total cost per lb. in orbit can be determined as a function of growth rate. These costs include all operations associated with the appropriate launch vehicles. The cost per lb. in orbit based only on recurring costs is approximately $1000/lb. to synchronous equatorial orbit and $120/lb. to low earth orbit.

For a given growth program the number of pounds required in orbit to produce one unit of product can be determined. This factor combined with the appropriate cost from Figure 5-7 produces the total transportation cost per unit of product. Therefore comparisons between alternate modes of production can be made on a per unit basis or on a total annual expenditure basis. By proper combination of the results in this section with additional transportation and other operating costs associated with a potential growth product, the methodology presented in section 5.4 can be applied to evaluate the potential of growth commodities or industrial processes for new space applications.

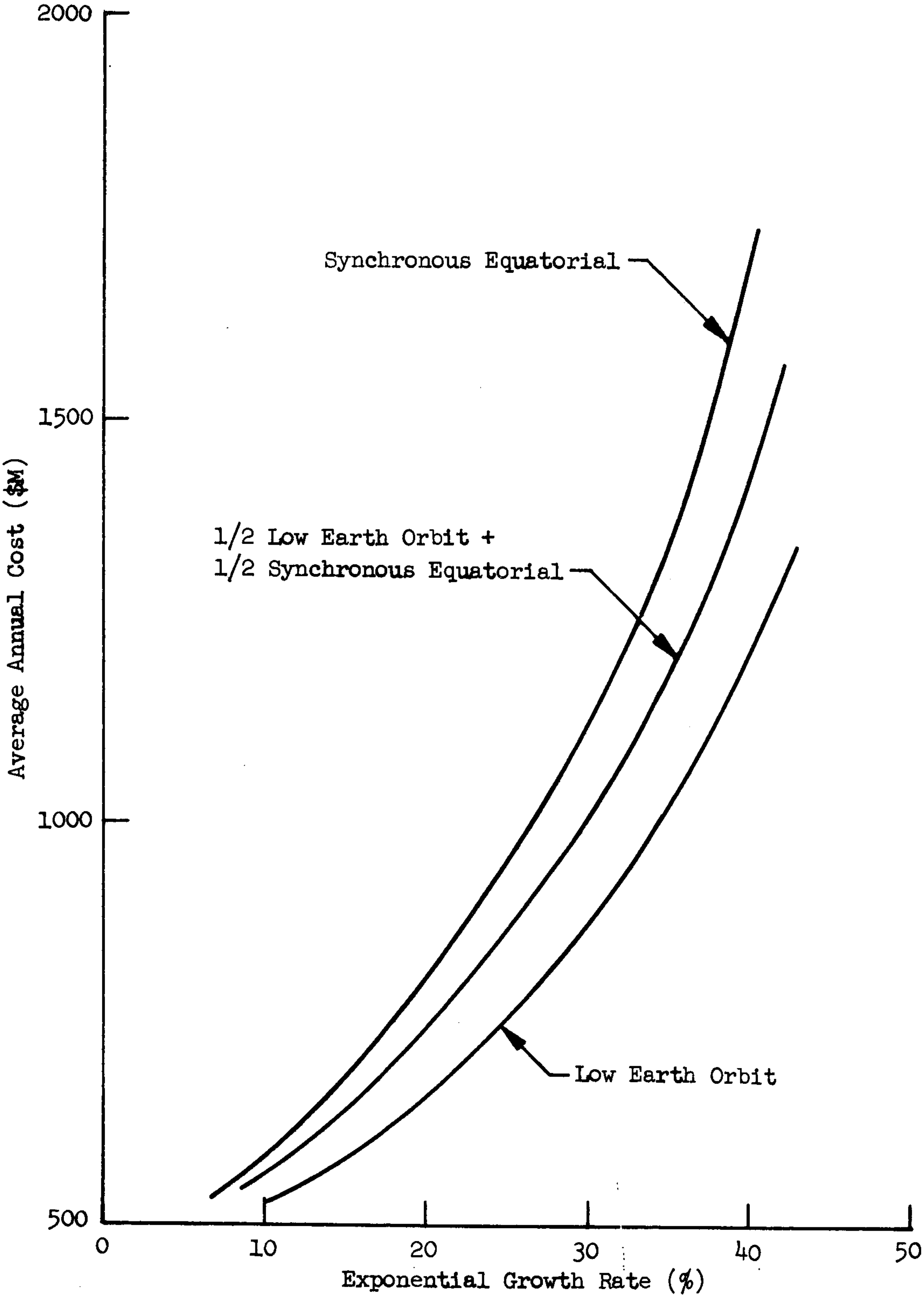

Fig. 5-6 Average Annual Transportation Costs

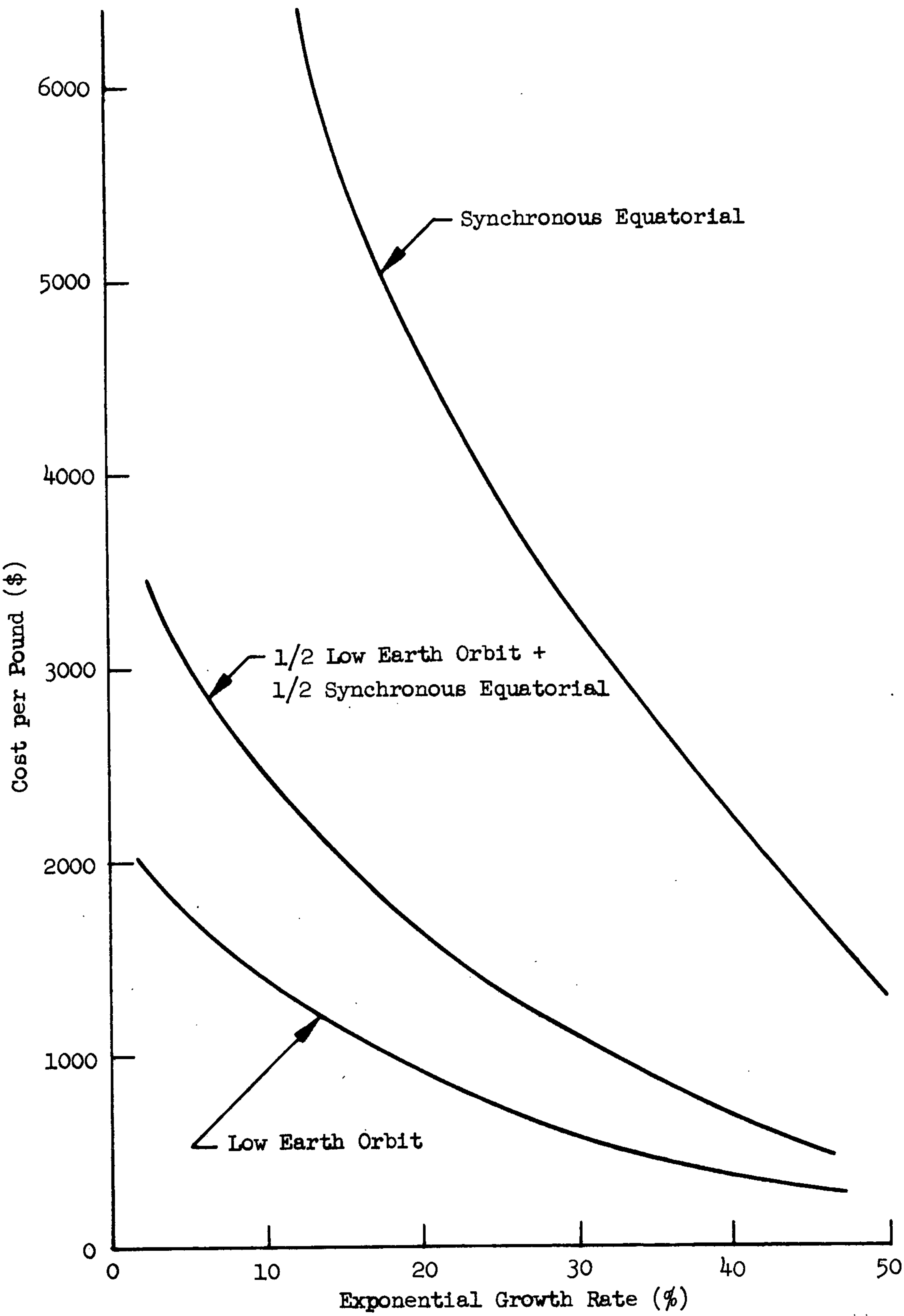

Fig. 5-7 Total Average Cost per Pound in Orbit

Section 6

CONCLUDING REMARKS

6.1 MODEL DEVELOPMENT

During this phase of effort the previously developed model was extended to include the following additional capabilities:

(1) Expanded output flexibility to provide better comparative data for evaluating total space programs including alternate mission models, program categories, systems, and external economics.

(2) Three parameter lognormal distributions for program elements to better fit historical cost uncertainty data for over 100 advanced systems

(3) Improved statistical correlation between cost elements of an advanced program to more accurately estimate future program costs

6.2 NEW PROGRAM DIRECTION DECISION METHODOLOGY

Also during this study phase preliminary criteria and related analytic procedures were established for identifying significant new space program directions. These criteria and procedures can be applied in two areas, namely (1) more effective accomplishment of existing services and industrial applications and (2) the utilization of space for new national requirements which can gain public acceptance. The second area is of particular interest and the defined criteria emphasize the capability to analyze growth commodities and services.

Example production runs were made on the developed model using generic growth applications superimposed on varied levels of space traffic models. Under these conditions the potential utilization of space for new applications can be analyzed in realistic perspective. Thus the advantages that a potential application can gain from the existing investment in national space program plant and contemporary on-going programs can be quantitatively evaluated; and the profit and benefit gain vs. cost of the new application can be determined. Benefit gain can include environment improvement. Further, the optimal model is uniquely suited to examing the effects of varied traffic levels for the reusable space transportation system and the synergistic result of complementary applications.

6.3 SUMMARY OF RESULTS

The following are the significant results of this period of study. Supporting details are provided in prior sections of this report.

- Extended Model Capability - The inclusion of additional features increase the capabilities available for the analyses of the national space program.
- Data Collection - Upgraded performance and cost data have been collected for space program elements and mission models. A method of estimating payload and other mission related data has been provided.
- Production Exercising - The model has been exercised on large scale production runs. The use of the deterministic and probabilistic options in addition to parameterized external economics (appropriation levels and inflation) provide sensitivity data for rapid assessment by the analyst. The capability of the model to define the varying composition of mission categories within the total program as functions of alternative system approaches (including alternate concepts for

both reusable and expendable vehicles) and economic variations has been demonstrated.

- Certainty of Results - The probabilistic model option provides the capability to allocate resources to the national space program with any selectable degree of certainty that cost growth will not cause program overruns.

- Mission Models - A new concept has been applied in defining mission models over extended future periods (e.g. 20 years). Firmly planned missions are entered in detail for the near term; missions farther in the future are included in terms of averaged payload and performance characteristics compatible both with the mission requirements and an advanced technology state. Using this method a balanced future space program can be evaluated including all mission categories.

- Criteria for New Space Directions - Criteria and an evaluation methodology were developed for identifying potential new utilizations of space (sections 5 and 6.2). Effort in this new area provides a systematic method for examining new space applications which can exploit the national investment in space and evaluate new concepts having significant potential for increasing national productivity.

- Application to Other Resource Allocation Areas - The adaptability of the developed space resource allocation model was assessed for application to other areas. It was determined that the model can readily be adapted to new problems by particularizing parameters to the new area and making minor modifications to model analytics.

The new commodity decision methodology is similiarly applicable. The combination of the model and the decision methodology provide a particularly effective technique for evaluating the viability of new commodities and industrial ventures.

6.4 APPLICATIONS

The extension of the model, its production exercising, and the development of decision criteria and analytic methodology for new utilizations of space suggest two areas of study which can exploit the results of this present study.

(1) Over 50 growth commodities and industrial applications have been identified. Utilize the developed model and the decision criteria to evaluate these for potential space implementation. Emphasize areas which have or can gain public acceptance and can take advantage of the national space investment.

(2) Extend the model for use in general optimal resource allocation problems. Demonstrate this capability in one or more sample applications.

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